

# Intermediate-Mass Black Holes

M. Coleman Miller<sup>1</sup> and E. J. M. Colbert<sup>2</sup>

<sup>1</sup>Department of Astronomy, University of Maryland  
College Park, MD 20742-2421  
miller@astro.umd.edu

<sup>2</sup>Department of Physics and Astronomy, Johns Hopkins University,  
Baltimore, MD 21218  
colbert@pha.jhu.edu

## ABSTRACT

The mathematical simplicity of black holes, combined with their links to some of the most energetic events in the universe, means that black holes are key objects for fundamental physics and astrophysics. Until recently, it was generally believed that black holes in nature appear in two broad mass ranges: stellar-mass ( $M \sim 3 - 20 M_\odot$ ), which are produced by the core collapse of massive stars, and supermassive ( $M \sim 10^6 - 10^{10} M_\odot$ ), which are found in the centers of galaxies and are produced by a still uncertain combination of processes. In the last few years, however, evidence has accumulated for an intermediate-mass class of black holes, with  $M \sim 10^2 - 10^4 M_\odot$ . If such objects exist they have important implications for the dynamics of stellar clusters, the formation of supermassive black holes, and the production and detection of gravitational waves. We review the evidence for intermediate-mass black holes and discuss future observational and theoretical work that will help clarify numerous outstanding questions about these objects.

*Subject headings:* black hole physics — (Galaxy:) globular clusters: general — gravitational waves — stellar dynamics — X-rays: binaries

## 1. Introduction

Isolated black holes are the simplest macroscopic objects in nature, being completely described by just their gravitational mass, angular momentum, and electric charge, and only the mass and angular momentum are likely to be significant for any real black hole. As a result, the mathematical theory of black holes has been developed extensively (e.g., Chandrasekhar 1992) and properties of black holes such as Hawking radiation (Hawking 1976) are now being compared with predictions of string theory (e.g., Maldacena, Strominger, & Witten 1997).

Direct evidence for the existence of black holes has been slower to accumulate. Starting in the early 1970s with the discovery of a number of bright X-ray sources using the *Uhuru* satellite

(for a summary of this mission and sources see Forman et al. 1978), it has become progressively clearer that there are many binaries in our Galaxy and others that consist of a black hole of mass  $\sim 3 - 20 M_{\odot}$  accreting matter from a stellar companion. Black holes in this mass range, called stellar-mass black holes, are thought to have been born during the core collapse of a massive star. Convincing evidence that an object is a black hole requires that its mass be definitely established to be in excess of  $3 M_{\odot}$ , which is an extremely conservative upper limit to the mass of a neutron star (e.g., Kalogera & Baym 1996). Such mass estimates require careful radial velocity measurements of the companion star. At this time, 17 X-ray emitting compact objects are known to have masses in excess of the neutron star maximum (Orosz 2002). In some cases the orientation of the orbit and nature of the companion allow more precise estimates of the mass. These mass estimates currently range from  $\sim 4 M_{\odot}$  (GRO 0422+32) to  $14 \pm 4 M_{\odot}$  (GRS 1915+105; see Orosz 2002 for an updated table).

Independent evidence for the existence of supermassive black holes in the centers of galaxies has also become compelling. The tremendous luminosities and small sizes of active galactic nuclei (AGN) led early on to suggestions that these are powered by accretion onto black holes (Zel’dovich & Novikov 1964; Salpeter 1964). This model is now solidly established by many observations. Not long after the discovery of quasars, Lynden-Bell (1969) realized that many “dead” quasars would exist as supermassive black holes in nearby galaxies. This has now been confirmed by high-precision monitoring of stars. Multiple stellar orbits have been tracked around the  $\sim 3 \times 10^6 M_{\odot}$  black hole in the center of our Galaxy (e.g., Eckart & Genzel 1996; Ghez et al. 1998; Ghez et al. 2000; Eckart et al. 2002; Schödel et al. 2002; Ghez et al. 2003a,b), following up earlier observations of gas motion in the Galactic center that suggested a strong concentration of mass (e.g., Lacy et al. 1980; Genzel et al. 1985). Intriguingly, some of the specifics of the stellar distribution very near the Galactic center may be best explained by the presence of an intermediate-mass black hole (Hansen & Milosavljevic 2003). Recent observations of the pericenter passage of star S2 (Schödel et al. 2002) demonstrate that the mass is contained within a radius of  $6 \times 10^{-4}$  pc, far more compact than possible for a stable distribution of individual objects. The spectral energy distribution of AGN can extend well into the gamma ray regime, implying relativistic motion. Finally, relativistically broadened Fe K $\alpha$  lines have been seen from several AGN, and their detailed properties may suggest rapid rotation as well as confirming the deep potential well around black holes (e.g., Iwasawa et al. 1996; Dabrowski et al. 1997; Wilms et al. 2001; Fabian et al. 2001).

The formation of supermassive black holes is not as well established as the formation of stellar-mass black holes. The high luminosity of many AGN indicates that they are obtaining matter from an accretion disk, and it is possible that this is their primary mode of growth. However, it is also possible that dynamical interactions or relativistic instabilities could contribute to the growth of supermassive black holes (e.g., Begelman, Blandford, & Rees 1984). Interestingly, it has recently been established that the mass of a supermassive black hole is tightly correlated with the velocity dispersion of the stars in the host galaxy (e.g., Ferrarese & Merritt 2000;

Gebhardt et al. 2000a; Merritt & Ferrarese 2001a,b; Tremaine et al. 2002), even though those stars are well beyond the radius of gravitational influence of the central black hole. This may imply a deep connection between the formation of galaxies and the formation of supermassive black holes.

It has long been suspected that black holes of masses  $\sim 10^2 - 10^4 M_\odot$  (intermediate-mass black holes, or IMBHs) may form in, for example, the centers of dense stellar clusters (e.g., Wyller 1970; Bahcall & Ostriker 1975; Frank & Rees 1976; Lightman & Shapiro 1977; Marchant & Shapiro 1980; Quinlan & Shapiro 1987; Portegies Zwart et al. 1999; Ebisuzaki et al. 2001). However, for many years there was no observational evidence for such a mass range. In roughly the last decade, X-ray and optical observations have revived this possibility. If such black holes exist, especially in dense stellar clusters, they have a host of implications, particularly for cluster dynamical evolution and the generation of gravitational waves.

Here we discuss the evidence for and implications of intermediate-mass black holes. There are two types of data that suggest the existence of IMBHs. First, there are numerous X-ray point sources, called ultraluminous X-ray sources (ULXs), that are not associated with active galactic nuclei yet have fluxes many times the angle-averaged flux of a  $M < 20 M_\odot$  black hole accreting at the Eddington limit. Second, several globular clusters show clear evidence for an excess of dark mass in their cores. At present, we regard the X-ray evidence as more convincing, hence we discuss ULXs in detail in § 2. We discuss globular cluster observations in § 3, as well as models with and without IMBHs. In § 4 we describe proposed formation mechanisms for intermediate-mass black holes. In § 5 we go through models proposed for ULXs that do not involve IMBHs, and evaluate several concerns that have been raised about the IMBH hypothesis. In § 6 we discuss the implications of IMBHs if they exist, with a focus on gravitational radiation. We conclude in § 7 by listing a number of important observations and theoretical calculations that will clarify our understanding of these objects.

## 2. Ultra-Luminous X-ray Sources

Historically, most of the first detected bright X-ray sources were identified as accreting neutron stars or black holes in our Galaxy (Giacconi et al. 1971). However, it is not necessarily true that most neutron stars and black holes are also strong X-ray sources. Isolated black holes emit a negligible amount of electromagnetic radiation, and they are therefore very difficult to study. If instead the black hole is “active” (i.e., accreting any significant amount of matter), it is usually an X-ray source, and the X-ray emission may be used to diagnose the physical properties of the accretion. In X-ray sources with moderate to high accretion rates, the accreting matter is believed to form a dense accretion disk surrounding the black hole. Geometrically thin disks are usually thought to have an inner edge near the innermost stable circular orbit, which is  $3R_s$  for a non-spinning (Schwarzschild) black hole. Here,  $R_s$  is the Schwarzschild radius, which is directly

proportional to the mass of the black hole  $M$ :

$$R_s = 2 \frac{GM}{c^2} \approx 2.9 \left( \frac{M}{M_\odot} \right) \text{ km.} \quad (1)$$

Note that magnetic links from the disk inside the innermost orbit could allow energy extraction even inside the innermost stable circular orbit, as might interaction with the spin of the black hole: for theoretical work see Krolik (1999); Gammie (1999); Agol & Krolik (2000); Reynolds & Armitage (2001), and for possible observational evidence see Wilms et al. (2001); Miller et al. (2002b); Reynolds & Nowak (2003). For a spinning (Kerr) black hole, the last stable circular orbit, and thus the standard inner disk radius, ranges from 0.5 to 4.5  $R_s$ , depending on the black hole spin and the sense of disk rotation (prograde or retrograde, e.g. Ori & Thorne 2000).

Gas in the inner disk interacts with itself, releasing energy and transporting angular momentum, and much of the thermal energy is emitted in X-rays (for stellar-mass black holes) and ultraviolet light (for supermassive black holes in AGNs). Other physical processes in coronal gas near the black hole also produce significant amounts of X-ray emission, perhaps dominating the observed X-ray flux in AGNs. Much of what we know about black holes comes from observations of “active” ones, and therefore the study of black holes and the study of accretion-powered X-ray sources are very closely linked.

## 2.1. Isotropic Emission and the Eddington Luminosity

Since one usually has no information about the flux radiation pattern  $f_X(\Omega)$  emitted by the X-ray source, it is common to assume an “isotropic” X-ray luminosity  $L_X$ , as if the radiation pattern is uniform in all directions:

$$L_X = \iint d\Omega R^2 f_X(\Omega) = 4\pi R^2 F_X, \quad (2)$$

where  $F_X$  is the observed X-ray flux,  $R$  is the distance to the source, and  $f_X(\Omega)$  is the flux emitted in a particular direction.

The luminosity generated by accretion onto a black hole exerts an outward radiation force on the accreting matter. If the radiative acceleration exceeds the acceleration of gravity, accretion is halted and no luminosity is generated. For accretion around a black hole, in which the matter is highly ionized and electron scattering is the most important form of opacity, a source of mass  $M$  that accretes and radiates *isotropically* therefore cannot have a luminosity that exceeds the Eddington luminosity

$$L_E = \frac{4\pi GMm_p}{\sigma_T} = 1.3 \times 10^{38} \left( \frac{M}{M_\odot} \right) \text{ erg s}^{-1}, \quad (3)$$

where  $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$  is the Thomson scattering cross section. We have assumed pure ionized hydrogen here;  $L_E$  is slightly greater for a cosmic composition. Therefore, if isotropy holds, an observed flux places a lower limit on the mass of an accreting black hole.

If instead the accretion or radiation are anisotropic, there is no fundamental reason why the luminosity cannot exceed  $L_E$  by an arbitrary factor. Beaming of the radiation can produce a flux  $f_X(\Omega)$  in a particular direction that is much greater than the average over all angles. We will discuss anisotropic models for ULXs further in § 5, but for now we concentrate on isotropic models.

## 2.2. Definitions and Nomenclature

If we consider stellar-mass BHs to have a maximum mass of  $\approx 20 M_\odot$  (e.g. Fryer & Kalogera 2001), then the Eddington luminosity of an “intermediate-mass” BH is  $\gtrsim 3 \times 10^{39} \text{ erg s}^{-1}$ . This limits the bolometric energy output of the object. The X-ray luminosity in the 2–10 keV band, for example, will be a factor of a few–10 times smaller, and it will be dependent on the metallicity as well. The lower limit to the X-ray luminosity for a ULX is defined to be  $10^{39.0} \text{ erg s}^{-1}$ . In practice, this limit distinguishes the “normal” BH X-ray binaries (XRBs), with  $L_X \lesssim 10^{39.0} \text{ erg s}^{-1}$  found in our Galaxy from the intriguingly more luminous ULXs found in some nearby galaxies. The upper limit for  $L_X$  for ULXs is not specified, but usually objects have  $L_X < 10^{40.5} \text{ erg s}^{-1}$ , and most of them have  $L_X < 10^{40.0} \text{ erg s}^{-1}$ . Quasars, supernovae, and other galaxy nuclei are usually omitted, although some workers (e.g. Roberts et al. 2001) include X-ray luminous supernovae.

Ultra-Luminous X-ray sources (ULXs) were named as such by several Japanese workers who analyzed spectra from the Japanese X-ray satellite ASCA (Mizuno et al. 1999, Makishima et al. 2000, Kubota et al. 2002). Here, “ultra-luminous” is gauged with respect to “normal” X-ray binaries. The term ULX is now widely used for these intriguing off-nuclear sources. Another term that is used is “Intermediate-luminosity X-ray Objects,” (IXOs), which simply indicates that their X-ray luminosities are intermediate between those of “normal” stellar-mass BH XRBs, and AGNs.

## 2.3. A Historical Background: ULXs in the Einstein Era

ULXs were observed as early as the 1980s, when extensive X-ray observations of external galaxies were first performed with the Einstein satellite. These studies revolutionized the understanding of black holes and their X-ray sources. Many of the nearby AGNs in Seyfert galaxies were expected to have very luminous X-ray nuclei, but it was a surprise to find that many “normal” spiral galaxies also had central X-ray sources (see Fabbiano 1989 for a review). These X-ray sources had X-ray luminosities  $\gtrsim 10^{39} \text{ erg s}^{-1}$ , well above the Eddington value for a single neutron star or a stellar-mass black hole. The spatial resolution of the most widely used instrument on Einstein (the Imaging Proportional Counter, or the IPC, FWHM  $\sim 1'$ ) is  $\gtrsim 1 \text{ kpc}$  for typical galaxy distances  $\gtrsim 4 \text{ Mpc}$ , so it was not clear whether these sources were single or multiple objects, or whether they were really coincident with the nuclei. We show some IPC images of the less ambiguous cases in Figure 1. Some possibilities included a single supermassive

black hole with a low accretion rate, a black hole with a normal accretion rate and super-stellar mass, hot gas from a nuclear starburst, groups of  $\gtrsim 10$  “normal” X-ray binaries (e.g. Fabbiano & Trinchieri 1987), or very luminous X-ray supernovae (see Schlegel 1995). The supermassive black hole scenario was not very well supported since there was not typically any other evidence for an AGN from observations at optical and other wavelengths. Another possibility was that the errors in the galaxy distances were producing artificially large X-ray luminosities. The nearest of these interesting X-ray objects is located in the center of the Local Group spiral galaxy M33 (see Long et al. 1981). Several other Einstein observations of similar objects are reported in Fabbiano & Trinchieri (1987), and a summary of Einstein observations are given in the review article by Fabbiano (1989). Unfortunately, the X-ray spectral and imaging capabilities of the IPC instrument were not generally good enough to distinguish between the possible scenarios. Even so, it was realized that these very luminous X-ray sources were not uncommon in normal galaxies, and that they deserved further attention.

#### 2.4. ROSAT observations of ULXs

The ROSAT satellite was launched into orbit in 1990, and began producing X-ray images at  $\sim 10\text{--}20''$  resolution. The highest resolution instrument was the High Resolution Imager (HRI; PSF  $\approx 10''$ ). The sensitivity and spatial resolution were a significant improvement over the

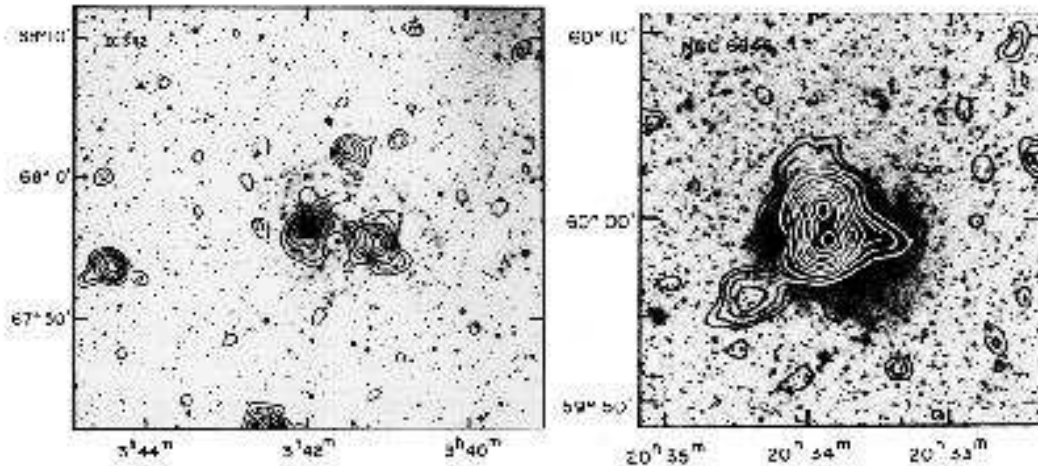


Fig. 1.— Contours of the Einstein IPC X-ray emission from two nearby face-on spiral galaxies (IC 342, on the left, and NGC 6946, on the right). Both nuclei are quite luminous. Even with only  $\sim 1'$  resolution, it is obvious that there are two very luminous, off-nuclear X-ray sources in IC 342 (west and north of the nucleus), and one in NGC 6946 (north of the nucleus). Reprinted with permission from Fabbiano & Trinchieri (1987).

Einstein IPC, many more ULXs were discovered, and several surveys were done. It was soon found that some of these luminous X-ray sources were not coincident with the galaxy nucleus. For example, in Figure 2, we compare Einstein IPC and ROSAT HRI (High Resolution Imager) images of the central X-ray sources in the spiral galaxy NGC 1313. After registering the ROSAT image with the X-ray bright supernova 1978K (X-3), Colbert et al. (1995) found that the central Einstein source was actually located  $\sim 1'$  ( $\sim 1$  kpc) NE of the center of the nuclear bar. Some of the other Einstein X-ray sources, are, however, still consistent with being located in the galaxy nucleus. For example, even with Chandra accuracy ( $1''$ ), the M33 source is still coincident with the nucleus of the galaxy, although it is not thought to be an AGN, since the dynamic mass at that position is too small and the X-ray and optical properties are more consistent with it being an XRB-like object (Gebhardt et al. 2001, Long et al. 2002, Dubus & Rutledge 2002).

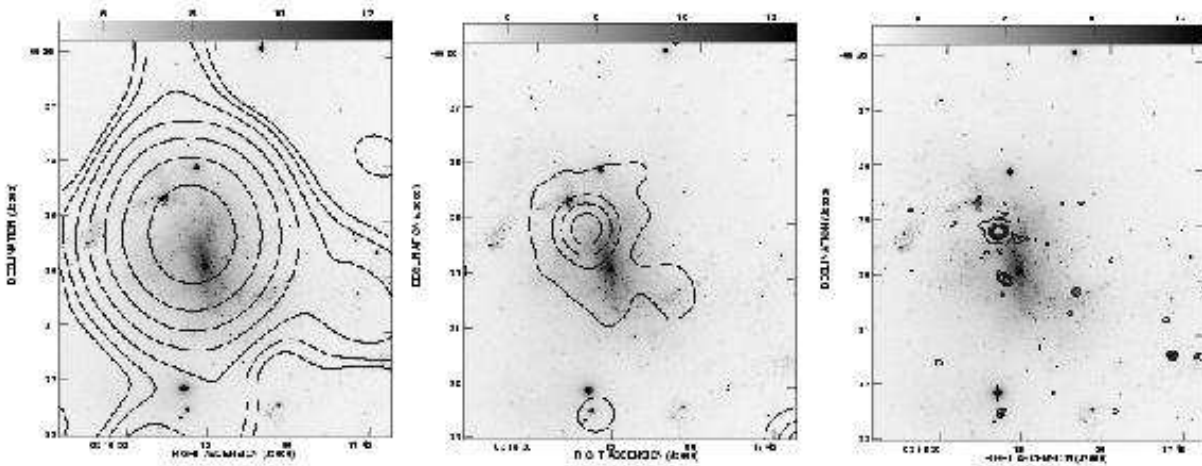


Fig. 2.— Comparisons between X-ray Instruments. The greyscale image shows optical I-band emission of the nearby face-on spiral galaxy NGC 1313 (from Kuchinski et al. 2000). The contours show X-ray emission near the center of the galaxy from an Einstein IPC image (left), a ROSAT HRI image (center), and a Chandra ACIS image (right). Note the ambiguity of the location of the ULX disappears as the resolution gets better, and many more X-ray sources are found with the newer instruments on ROSAT and Chandra. The I-band image was retrieved from NED, the Einstein and ROSAT images are from NASA’s HEASARC, and the ACIS image was kindly provided by G. Garmire.

The PSPC spectrometer on ROSAT had much better spectral resolution than the Einstein IPC, but it only covered soft X-ray energies (0.2–2.4 keV), and so was of limited use for diagnosing ULX emission models. However, much progress was made from surveys done with the ROSAT HRI. Four large HRI surveys of nearby galaxies (Colbert & Mushotzky 1999, Roberts & Warwick 2000, Lira, Lawrence & Johnson 2000, and Colbert & Ptak 2002) showed that off-nuclear luminous X-ray sources were actually quite common – present in up to half of the galaxies sampled. At

the time of the first three surveys, ULXs were not a well defined class of objects. Roberts & Warwick (2000), Colbert & Ptak (2002), Roberts et al. (2002a), and ongoing work by Ptak & Colbert indicate that ULXs, as we have defined them in section 2.2, are present in one in every five galaxies, on average. When ROSAT survey work started showing that ULXs, and thus possibly IMBHs, were quite common, ULXs and IMBHs became a popular topic of study.

#### 2.4.1. A Census of ULX Luminosities and BH Masses

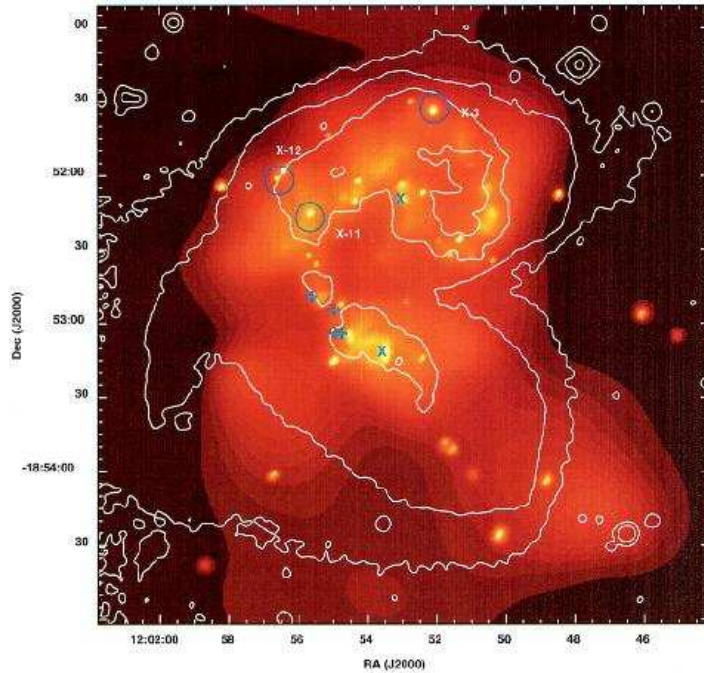


Fig. 3.— Adaptively smoothed Chandra ACIS image of the “Antennae” galaxies, showing the ULXs and very luminous X-ray sources. The white contours show the optical emission levels of the galaxies. The two nuclei NGC 4038 and NGC 4030 are marked with crosses. Reprinted with permission from Fabbiano et al. (2001).

As described above, IMBHs with  $M \gtrsim 20 M_{\odot}$  have  $L_E \gtrsim 3 \times 10^{39} \text{ erg s}^{-1}$ . In the Colbert & Ptak (2002) catalog of 87 ULXs, 45 objects have 2–10 keV X-ray luminosities  $L_X > 3 \times 10^{39} \text{ erg s}^{-1}$ . Eleven objects have  $L_X > 10^{40} \text{ erg s}^{-1}$ , which corresponds to quasi-isotropic sources with masses  $M > 70 M_{\odot}$ . Thus, the potential for IMBHs is clearly present. Some galaxies, such as NGC 4038/9 (“The Antennae”) have  $\gtrsim 10$  ULXs with masses  $\gtrsim 10$ –(few)100 (by the Eddington argument), if the X-rays are not beamed (see Figure 3, and Fabbiano et al. 2001, but see also Saviane, Hibbard, and Rich 2003 for a closer distance to the Antennae, which implies lower luminosities). The brightest ULX yet observed, in the galaxy M82 (see Figure 4, and Ptak & Griffiths 1999; Matsushita et al. 2000; Kaaret et al. 2001), has a peak X-ray luminosity of



$9 \times 10^{40} \text{ erg s}^{-1}$  (Matsumoto et al. 2001), implying a mass  $M > 700 M_{\odot}$  by Eddington arguments. This is well beyond the expected  $\sim 100 - 200 M_{\odot}$  upper limit of stellar mass in the current universe (see the introduction to § 4). In addition, even a star that starts its life with a high mass may lose most of it to winds and pulsations, leaving behind a black hole of mass  $M \lesssim 20 M_{\odot}$  if it forms with roughly solar metallicity (e.g., Fryer & Kalogera 2001). Objects of such mass must either have accumulated most of their matter by some form of accretion, or have formed in some other epoch of the universe.

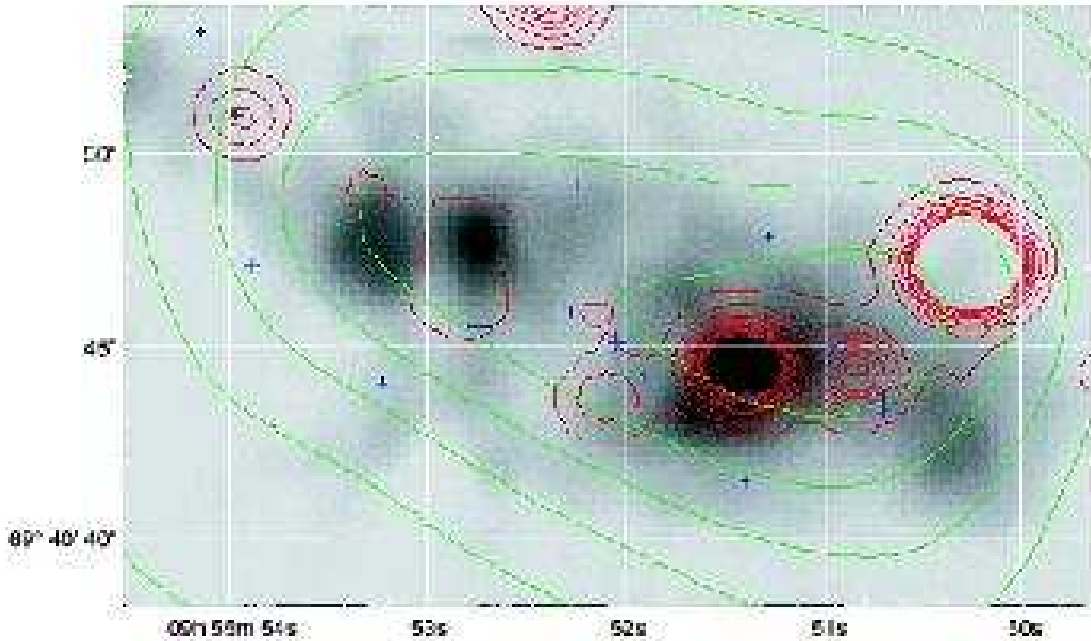


Fig. 4.— Gray-scale mid-infrared image of the central region of the edge-on irregular starburst galaxy M82. The dark contours show the X-ray emission, in particular the famous ULX at the far right of the image. The light contours are hard diffuse X-ray emission, and the crosses are radio sources. From Griffiths et al. (2000).

The possibility remains that these objects are under-luminous supermassive black holes. However, as we explore in section 2.4.2, the locations of the ULXs within the galaxies rule against masses more than  $\sim 10^6 M_{\odot}$  in many cases.

Although the Colbert & Ptak (2002) ROSAT HRI sample is the largest published ULX catalog (see Figure 5), an even larger number of ULXs have been found with Chandra. Swartz, Ghosh, & Tennant (2003), Swartz et. al (2003, in prog.) and Ptak & Colbert (2003, in prog.) are finding  $\sim 200-300$  ULXs from analyses of currently available Chandra archive data. This implies a factor of  $\sim 2-3$  times more potential IMBHs than the ROSAT surveys estimate.

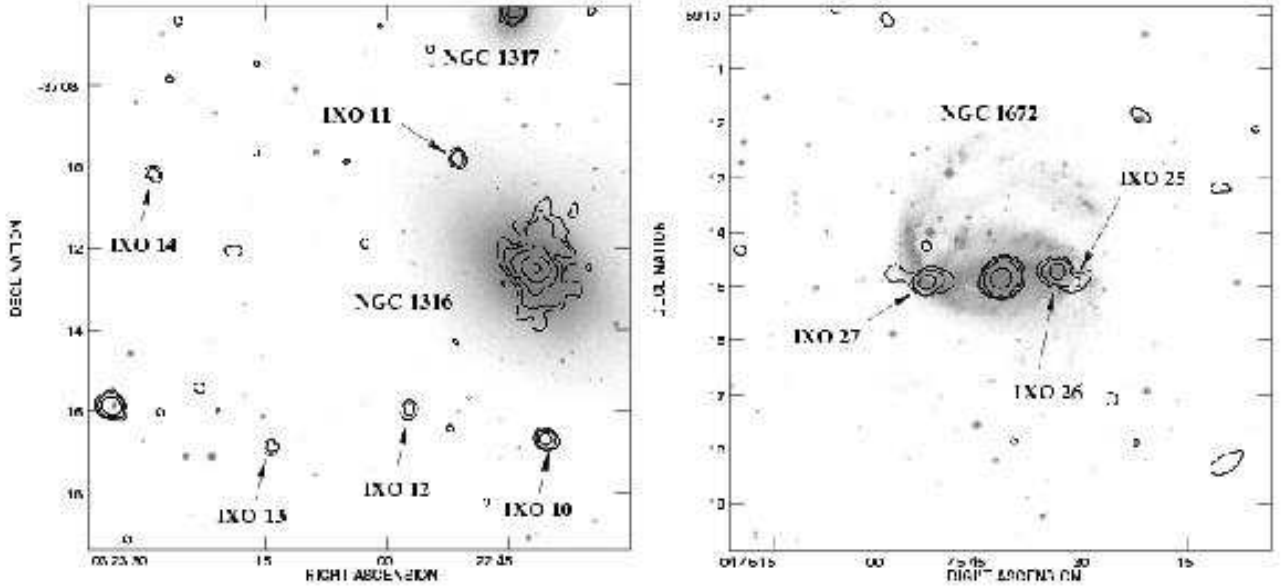


Fig. 5.— Two example galaxies with ULXs, from Colbert & Ptak (2002). On the left we show five of the six ROSAT HRI ULXs (IXOs) in the elliptical galaxy Fornax A (NGC 1316). On the right is the face-on barred spiral galaxy NGC 1672, which has two ULXs, both positioned at the end of the bar, straddling the nuclear X-ray source.

#### 2.4.2. Location in Galaxies

Colbert & Ptak (2002) have compiled a list of all of the ULX candidates observed with the ROSAT HRI. This list shows that ULXs are found in both spiral and elliptical galaxies, as well as a few irregular galaxies. In spirals, Colbert & Mushotzky (1999) find that the bright X-ray sources are often near, but clearly distinct from, the dynamical centers of the galaxies, with an average projected separation of 390 pc (Figure 6). In ellipticals, the ULXs are almost exclusively in the halos of galaxies, and it is possible that these ULXs are distinct from those in spiral galaxies (Irwin, Athey & Bregman 2003). The off-center positions in spiral galaxies show that these are not under-luminous supermassive black holes, because an object of too large a mass would sink to the center via dynamical friction in much less than a Hubble time. More quantitatively, adopting equation (7-27) of Binney & Tremaine (1987), the dynamical friction time is

$$t_{\text{fric}} \approx \frac{5.0 \times 10^9 \text{ yr}}{\ln \Lambda} \left( \frac{r}{\text{kpc}} \right)^2 \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right) \left( \frac{M}{10^7 M_{\odot}} \right)^{-1} \quad (4)$$

where  $\sigma$  is the velocity dispersion,  $r$  is the distance from the dynamical center of the galaxy, and  $\ln \Lambda \sim 5 - 20$  is the Coulomb logarithm. For example, for the most luminous X-ray source in M82,

$t_{\text{fric}} \approx 10^{10} \text{ yr}(10^5 M_{\odot}/M)$ , for an assumed  $\sigma$  of  $100 \text{ km s}^{-1}$  (Kaaret et al. 2002). Thus, high masses are ruled out for ULXs that are near, but not located in, the nucleus. Technically, one must keep in mind an individual object could have a much larger mass if it were many kpc away from the galactic center, but it is usual and probably correct to assume that this is quite a rare occurrence.

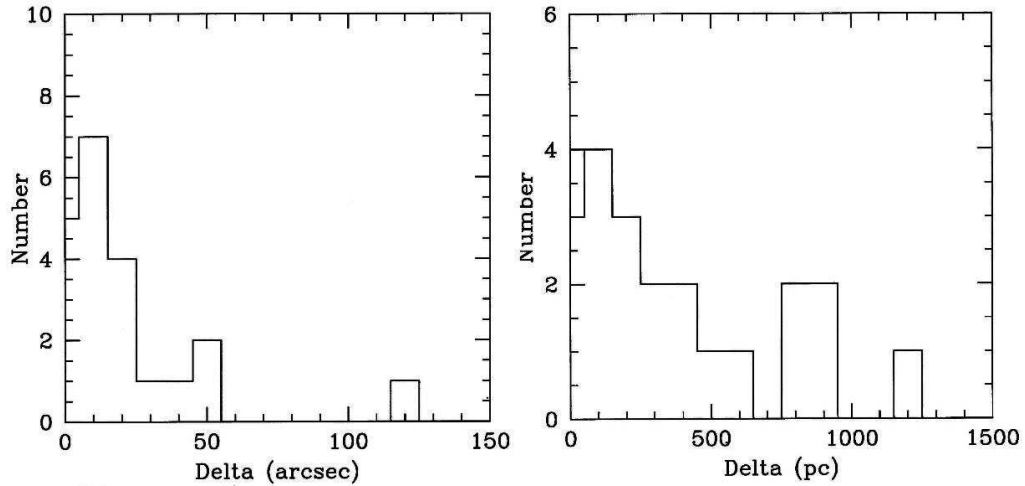


Fig. 6.— Histograms of offset of near-nuclear ROSAT HRI X-ray sources from nucleus, in arcseconds (left) and parsecs (right). From Colbert & Mushotzky (1999).

## 2.5. X-ray Energy Spectra of ULXs

As discussed previously, the earliest X-ray spectra of ULXs were obtained with the Einstein IPC instrument (e.g., Fabbiano & Trinchieri 1987). These spectral data were quite crude, however, and did not offer much in the way of diagnostics of the nature of the X-ray emission. Independent of any specific physical models, state transitions have been observed from some ULXs (e.g., Kubota et al. 2001 observed transitions between soft and hard spectra for two sources in IC 342). These state transitions reinforce the identification of ULXs with accreting black holes, although the transition behavior is complicated (see the end of § 2.7). More detailed inferences, however, depend on the spectral model used. A popular ULX model for ASCA spectra was the multi-color disk (MCD) blackbody model, since it was commonly used to fit X-ray spectra of “normal” BH XRBs.

### 2.5.1. The Multi-color Disk Blackbody Model

In the MCD model, each annulus of the accretion disk is assumed to radiate as a blackbody with a radius-dependent temperature, as modified by a spectral correction factor (Mitsuda et al. 1984). The spectral flux  $f(E)$  can be written as:

$$f(E) = \frac{\cos \theta}{R^2} \int_{r_{in}}^{r_{out}} 2\pi r B_E(T) dr, \quad (5)$$

where  $\theta$  is the angle of the disk axis with respect to the line of sight,  $R$  is the distance to the source, and  $B_E(T)$  is the Planck function at energy  $E$ . Since  $T(r) \propto r^{-3/4}$  for an assumed thin disk, the flux can also be written in terms of  $T$ :

$$f(E) = \frac{8\pi r_{in}^2 \cos \theta}{3R^2} \int_{T_{in}}^{T_{out}} \left( \frac{T}{T_{in}} \right)^{-\frac{11}{3}} B_E(T) dT. \quad (6)$$

In this model, the inferred temperature  $T_{in}$  of the innermost portion of the disk is related to the mass of the black hole:

$$kT_{in} \approx 1.2 \text{ keV} \left( \frac{\xi}{0.41} \right)^{1/2} \left( \frac{\kappa}{1.7} \right) \alpha^{-1/2} \left( \frac{\dot{M}}{\dot{M}_E} \right)^{1/4} \left( \frac{M}{10 M_\odot} \right)^{-\frac{1}{4}} \quad (7)$$

(e.g., Makishima et al. 2000, eq. 10). Here  $\kappa \approx 1.7$  is a spectral hardening factor,  $\xi \approx 0.4$  is a factor that takes into account that the maximum temperature occurs at a radius larger than the radius of the innermost stable circular orbit, and  $\alpha = R_{in}/(6GM/c^2)$  is unity for a Schwarzschild spacetime and  $\alpha = 1/6$  for prograde orbits in a maximal Kerr spacetime. Thus, if  $T_{in}$  inferred from MCD fits is representative, one expects lower temperature from accreting IMBH than from accreting stellar-mass black holes. Some detailed aspects of the application of the MCD model to ULX spectra are given in Makishima et al. (2000).

### 2.5.2. ASCA Spectral Modeling of ULXs and the “high temperature” Problem

Although ASCA had a poor PSF (FWHM  $\sim 1'$ ), it had far better sensitivity and spectral resolution than the Einstein IPC, and had much wider spectral coverage (0.4–10 keV) than the ROSAT PSPC. Therefore, substantial progress was made using ASCA observations of ULXs in nearby galaxies. ULX ASCA spectra are often modeled with a (soft) MCD component for the disk emission, plus a (hard) power-law component, which is presumed to be Comptonized disk emission (e.g. see Takano et al. 1994). As for Galactic BH XRBs, the power-law photon index  $\Gamma$  was noticed to be hard ( $\Gamma \approx 1.8$ ) in ULX low-flux states, and soft ( $\Gamma \approx 2.5$ ) in ULX high-flux states (e.g., Colbert & Mushotzky 1999, Kubota et al. 2002).

The implications of the MCD model were, however, problematic. While X-ray luminosities of  $\sim 10^{39-40} \text{ erg s}^{-1}$  are simply explained by an intermediate-mass black hole with sub-Eddington

accretion, the temperature  $kT_{in}$  (and radius  $r_{in}$ ) of the inner accretion disk, derived from MCD spectral fitting, are too high (low) for IMBHs (Mizuno et al. 1999; Colbert & Mushotzky 1999; Makishima et al. 2000; Mizuno, Kubota, & Makishima 2001). BH XRBs with stellar-mass black holes in our Galaxy typically have temperatures  $kT_{in} \approx 0.4 - 1$  keV, while ULXs have  $kT_{in} \approx 1.1 - 1.8$  keV, which is more consistent with LMXB micro-quasars in our Galaxy (e.g. Makishima et al. 2000). Given the large implied X-ray luminosities of ULXs, one might expect them to have lower  $kT_{in}$  (Eq. 7).

One explanation of the high-temperature problem is to suppose that the compact object is a stellar-mass BH with  $M \lesssim 10 M_{\odot}$ , and the X-ray emission is somehow beamed. This may well be the right model for some ULXs, but as we discuss below and in § 5.1 there are individual sources with circumstantial evidence against beaming as well as properties of ULXs as a class that are not yet fully addressed in beaming scenarios.

Mizuno et al. (1999), Makishima et al. (2000), and Ebisawa et al. (2001) offer several potential explanations for the “high temperature” problem. For example, it is possible that the BH is a Kerr IMBH, and the resulting frame dragging can shrink the inner radius of the accretion disk up to  $\approx 6$  times less than that of a Schwarzschild BH, for which  $r_{in} \gtrsim 3 R_s$ . Therefore,  $r_{in}$  can be smaller, and  $T_{in}$  is larger, as implied by the MCD models. Kerr models work well for ULXs as IMBHs (e.g., Mizuno et al. 2001), but imply very high disk inclination angles ( $i \gtrsim 80^\circ$ ), Ebisawa et al. 2001, Ebisawa et al. 2003).

One may also relax the assumptions of the “thin disk” model. For example, increasing  $\kappa$ , the ratio of the color temperature to the effective temperature, will yield higher masses (e.g. Shrader & Titarchik 1999), and so will increasing the correction factor  $\xi$ , which adjusts for the fact that  $T_{in}$  occurs at a slightly higher radius than  $r_{in}$  (see Kubota et al. 1998). The mass  $M$  is proportional to the product  $\kappa^2 \xi$ . Makishima et al. (2000) shows that  $\kappa^2 \xi$  has to differ largely from values for “normal” BH XRBs for the “high-temperature” problem to be solved.

Finally, one may completely abandon the physically thin accretion disk model. Abramowicz et al. (1988) and Watarai et al. (2000) show that very high accretion rates  $\dot{M} \gtrsim 10 L_E/c^2$  lead to an ADAF (Advection-Dominated Accretion Flow) solution (the so-called “slim disk” model), and that this can explain the  $r_{in} \propto T_{in}^{-1}$  relationship, found for MCD fits to ASCA spectra of ULXs (Mizuno et al. 2001). The slim-disk model allows masses to be slightly larger ( $\lesssim 10 - 30 M_{\odot}$ ), but not as large as  $\sim 100 M_{\odot}$ .

Much effort has gone into trying to explain why the MCD temperatures  $kT_{in}$  are so high for ULXs. However, it is possible that the ULXs are *not* well represented by a simple MCD disk model after all. For example, when simulated spectra of accretion disks are fit with MCD models,  $r_{in}$  and/or the disk accretion luminosity are very poorly estimated (e.g. Merloni et al. 2000, Hubeny et al. 2001). In addition, since the PSF of ASCA is so large, ASCA spectra can be contaminated by diffuse X-ray emission and by X-ray emission from other point sources positioned extraction regions, so that a single MCD model is inappropriate. In fact, as we now discuss, an increasing

number of ULX spectra from the smaller PSF instruments on Chandra and XMM now show much lower values of  $kT_{in} \sim 0.1$  keV.

### 2.5.3. XMM and Chandra Modeling of ULX X-ray Spectra

XMM and Chandra observations have the advantage that their spatial resolution ( $\approx 1''$  for Chandra,  $\approx 4''$  for the MOS2 camera on XMM) is good enough that contamination from other X-ray sources is not as problematic as it is for ASCA. They also have significantly better throughput than ASCA, which improves the signal to noise, and the bandwidth is also greater, which increases the flux from sources and allows detection of some ULXs that are absorbed in soft X-rays.

While ASCA ULX spectral models often required both MCD and power-law components, XMM and Chandra spectra are often fit with a single component (either MCD or power-law). This does not necessarily imply incompatibility between the ASCA data and the XMM/Chandra data, because of the different fields of view and sensitivities of the instruments. Some anomalous “super-soft” ULXs emit essentially all of their photons below a few keV, and do not always have MCD spectra, or power-law spectra with slopes typical of XRBs. For example, the spectrum of the super-soft ULX in NGC 4244 is better fit with a very steep ( $\Gamma \sim 5$ ) *power-law* model (Cagnoni et al. 2003). It is possible that these sources are quite different from most other ULXs.

In general, a simple power-law model with  $\Gamma \approx 2$  fits many XMM and Chandra ULX spectra well. For example, Roberts et al. (2001) show that the ULX in NGC 5204 is best fit by a power-law model. Similar results are found for the ULXs in NGC 3628 (Strickland et al. 2001) and the Circinus galaxy (Smith & Wilson 2001). Terashima & Wilson (2003) observed nine ULXs in M51 with Chandra and find that four are fit as well with a power law as with an MCD, two are fit better with a power law, and one is an emission line object in which a power law is assumed as a continuum, compared to two super soft sources where an MCD fits better than a power law. Roberts et al. (2002) find that three of the five brightest ULXs in NGC 4485/90 are better or equally well fit by a power-law model, compared to the MCD model. Foschini et al. (2002a) examined eight ULX candidates with XMM and find that the MCD model is never the best fit to the data; indeed, a power law fits better in 5 of the 8 cases, although the statistics are poor. Foschini et al. (2002a) also examined 10 other ULX candidates with data too poor for spectral fits. Two of the 18 total candidates have been identified with background sources. One of the power law sources (NGC 4698 ULX 1) has been identified with a background BL Lac object at redshift  $z = 0.43$  (Foschini et al. 2002b), and one of the sources with poor statistics (NGC 4168 ULX 1) has been identified with a background starburst nucleus at  $z = 0.217$  (Masetti et al. 2003). This injects a cautionary note that some ULXs that are best fit with power laws may actually be background nuclei.

There are also select cases for which a single MCD model is preferred over a power-law (e.g.,

M81 X-6 in Swartz et al. 2003, and also some objects listed in references above). It is likely that both MCD and power-law components are present, as in Galactic BH XRBs, but the quality of the spectra are not good enough to statistically require the weaker component (e.g. Humphrey et al. 2003).

An interesting result from the high-quality XMM ULX spectra is that, in some cases if an MCD component exists, its inferred temperature is much less than the value obtained from ASCA observations (some ROSAT observations also suggested two-component fits, consistent with an IMBH; see, e.g., Fabian & Ward 1993). For example, Miller et al. (2003a) analyzed XMM data of the brightest ULXs in NGC 1313, and found that a two-component fit is necessary (see Figure 7), with an inferred inner disk temperature  $kT_{\text{in}} = 0.15$  keV. In comparison, Colbert & Mushotzky (1999) analyzed two ASCA observations of NGC 1313 X-1; one had a hard spectrum, with an MCD best fit temperature of  $kT = 1.5$  keV, while the other was softer and more consistent with the recent XMM analysis. Some of the ASCA spectra did actually imply low values for  $kT_{\text{in}}$ . For example, the ULX NGC 5408 X-1 is best fit with a MCD temperature  $kT_{\text{in}} \approx 0.1$  keV (Colbert & Mushotzky 1999), and this is confirmed with Chandra (Kaaret et al. 2003). Similarly, the joint ROSAT+ASCA fit of the X-ray spectrum of the ULX in Ho II yields  $kT_{\text{in}} \approx 0.17$  keV (Miyaji et al. 2001). XMM spectra of four of the “Antennae” ULXs are also consistent with cool MCD disks with  $kT_{\text{in}} \sim 0.1$  keV, as are XMM spectra of M81 X-9 (Miller, Fabian, & Miller 2003). Di Stefano & Kong (2003) also report a number of quasi-soft sources with  $kT < 300$  eV that could be related to IMBHs.

It is important to recognize that these results do not *prove* that the inner disk temperature is cool, but they do demonstrate that the inference of high temperature from previous observations was unwarranted. Continuum spectra can often be fit with a variety of models, with widely different physical implications. Therefore, the current data and fits are consistent with the presence of intermediate-mass black holes, but do not require their presence (although attempts to infer the mass from continuum spectra are ongoing; see Shrader & Titarchuk 2003).

While power-law spectra are often assumed to be associated with low/hard states of BH XRBs like Cyg X-1, ASCA spectra of ULXs can also be fit with a strongly Comptonized disk model, associated with high/anomalous states in some Galactic BH XRBs (Kubota, Done, & Makishima 2002). As we discuss in section 2.7, there is growing observational evidence from Chandra and XMM observations that many ULXs may exhibit this anomalous high/hard behavior.

Although Fe K lines (6.4–7.0 keV) are not usually strong in BH XRBs, Strohmayer & Mushotzky (2003) found that the famous M82 ULX has a very broad Fe K line in an XMM spectrum. This is not easily explained by beaming models and thus provides indirect evidence for an IMBH scenario.

We should note here that nearly all of the X-ray spectral modeling results are derived for ULXs in spiral galaxies. This is primarily due to the larger distances of the nearby ellipticals (primarily in Virgo), and thus the lack of available photons for spectral analysis. If ULXs in

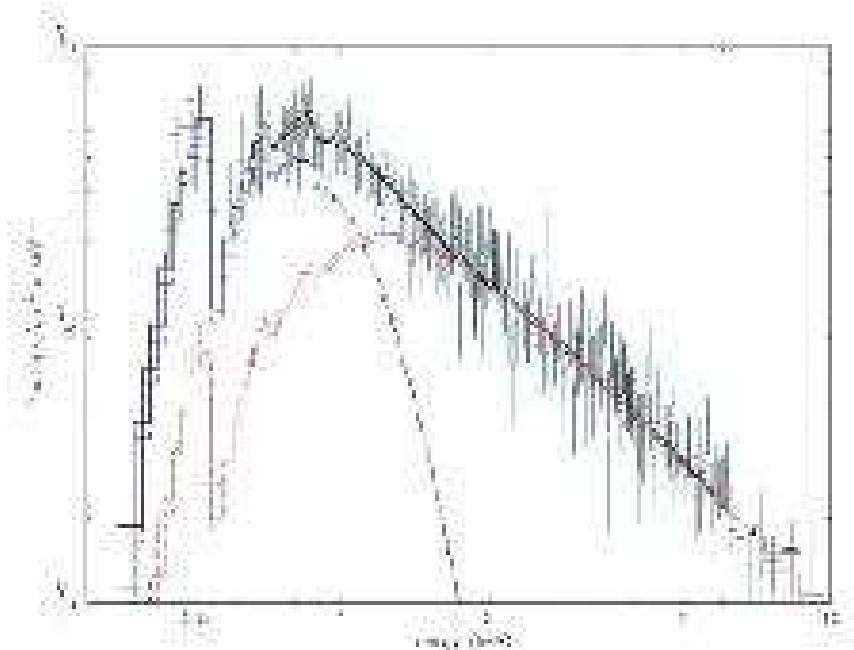


Fig. 7.— Unfolded XMM MOS spectrum of the ULX NGC 1313 X-1, along with components from an MCD model (blue) plus a power-law model (red). Absorption of soft X-rays below  $\sim 1$  keV is also modeled in the fit. Reprinted with permission Miller et al. (2003a).

ellipticals are indeed a different class than those in spirals (e.g. King 2002), we might expect a difference in their X-ray spectral properties. Pioneering work by Irwin et al. (2003) suggests, in fact, that ULXs in elliptical galaxies may have harder spectra than their counterparts in spirals.

## 2.6. ULXs and Host Galaxy Type

Now that Chandra is in full operation, its combined imaging and spectral capabilities have allowed the literature on ULXs to blossom. The excellent imaging sensitivities of Chandra and XMM ensure that one is likely to detect an ULX in observations of nearby galaxies  $\gtrsim 20\%$  of the time, for integrations of more than a few hours (Ptak 2001). Even short “snapshot” observations with Chandra and XMM have detected a significant number of ULXs (Sipior 2003, Foschini et al. 2002a).

Chandra observations of the merger pair NGC 4038/9 (“the Antennae”) revealed 8 ULXs (where the luminosities were estimated assuming a Hubble constant  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , Fabbiano, Zezas & Murray 2001). Since the Antennae have very high star-formation rates, this seemed to suggest that ULXs are directly related to the young star population. In fact, many of the well-studied ULXs are located in starburst galaxies: M82 (e.g. Kaaret et al. 2001 and



references therein), NGC 3628 (Dahlem et al. 1995, Strickland et al. 2001), and NGC 253 (K. Weaver, priv. comm.). Recently, a large number of potential ULXs have been reported in the Cartwheel galaxy by Gao et al. (2003), although variability studies are still needed to certify their ULX status. In addition, Zezas, Ward, and Murray (2003) report 18 ULXs in Arp 299. It was therefore conjectured that ULXs are a special type of high-mass BH XRB with beamed X-ray emission, and not IMBHs (King et al. 2001).

However, further observations showed that not all ULXs were found in starbursting, or even spiral galaxies. For example, Angelini et al. (2001) found several ULXs in a Chandra observation of the nearby giant elliptical galaxy NGC 1399 (see Figure 8). Sarazin, Irwin, & Bregman (2001) find bright point sources up to  $\approx 2.5 \times 10^{39}$  erg s $^{-1}$  in the elliptical galaxy NGC 4697, and conjecture that although only 20% of these sources are currently identified with globular clusters, all the LMXBs may have originated in globulars. In general, low-mass X-ray binaries in early-type galaxies are strongly correlated with globular clusters (Sarazin et al. 2003). A census of ULXs using all of the public ROSAT HRI data found that if one selects *only* those galaxies with detected ULXs, the elliptical galaxies with ULXs have a larger number per galaxy than do the spiral galaxies with ULXs (Colbert & Ptak 2002). The elliptical galaxy NGC 720 has nine ULXs, which is nearly as many that are found in the “Antennae” (Jeltema et al. 2003). Since ellipticals are also generally more massive than spirals, it does not imply that they are more efficient at producing ULXs, but it does imply that the high-mass BH XRB scenario does not work for all ULXs, since elliptical galaxies have virtually no young stars being formed.

As we discuss in the following sections, there are many possible scenarios that could explain ULXs, and intermediate-mass black holes remain an important contender. Chandra analyses of ULXs in elliptical galaxies show that their X-ray spectra may be harder than those in spiral galaxies (Irwin, Athey & Bregman 2003), corroborating that ULXs in ellipticals are distinct from those in spirals. As the Chandra and XMM data archives become more and more populated with spectral data for ULXs, we will be able to better study their spectral and temporal properties, and perhaps come to a better understanding of the underlying emission processes, and the physical properties of their black holes.

## 2.7. X-ray Variability of ULXs

It is possible that objects other than a single accreting black hole system could produce X-ray luminosities  $\geq 10^{39}$  erg s $^{-1}$ . For example, some very young ( $\lesssim 100$  yr) supernovae are known to emit  $\sim 10^{39}$  erg s $^{-1}$  in X-rays. However, their emission either fades or remains constant on timescales of  $\lesssim 1$  yr (cf. Schlegel 1995). A cluster of  $\sim 10$  or more “normal” luminous XRBs could also produce  $\sim 10^{39}$  erg s $^{-1}$ . However, neither of these scenarios would account for the random or periodic variability that has been observed in ULXs.

Colbert & Ptak (2002) estimate random variability of  $\gtrsim 50\%$  in over half of all ULXs,

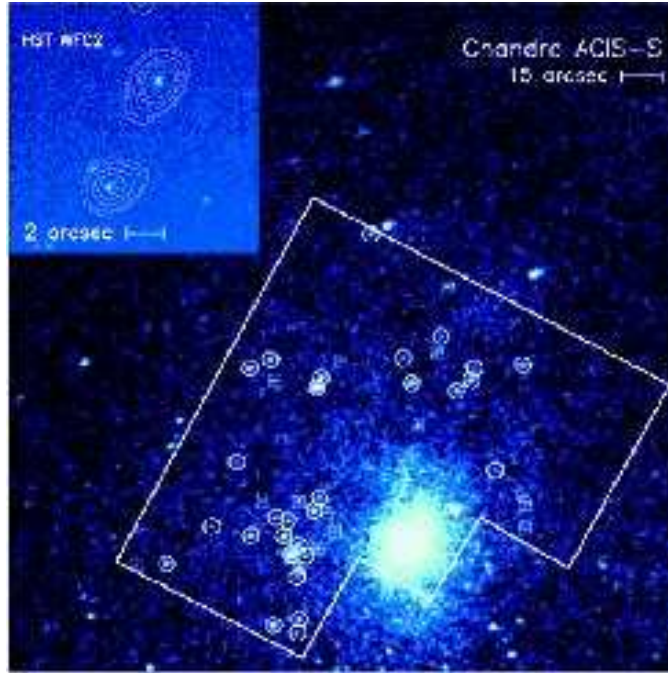


Fig. 8.— Smoothed Chandra ACIS-S image of the CD galaxy NGC 1399, with the HST WFPC2 FOV overlaid. The circles show the X-ray sources positions that are associated with globular clusters. Reprinted with permission from Angelini et al. (2001).

eliminating supernovae or XRB-clusters as likely scenarios. The brightest X-ray source in M82 brightened by a factor of 7 between two Chandra observations three months apart (Matsushita et al. 2000). Long-term variability of ULXs on timescales of months to years has been noted for ULXs in many nearby spiral galaxies: M81 (Ezoe et al. 2001, La Parola et al. 2001, Wang 2002, Liu et al. 2002), Ho II (Miyaji et al. 2001), M82 (Ptak & Griffiths 1999, Matsumoto & Tsuru 1999, Kaaret et al. 2001, Matsumoto et al. 2001), IC 342 (Sugiho et al. 2001, Kubota et al. 2001), Circinus (Bauer et al. 2001), NGC 4485/90 (Roberts et al. 2002a), M101 (Mukai et al. 2002), NGC 6503 (Lira et al. 2003), and M51 (Terashima & Wilson 2003).

Thus, variability on scales of months or longer is well-established. For periodic variability due to orbiting stars, Kepler’s third law predicts very short times for orbits near the BH:

$$P = 2.00 \times 10^{-10} \frac{(a/\text{km})^{\frac{3}{2}}}{(M/M_{\odot})^{\frac{1}{2}}} \text{days} = 3.65 \times 10^2 \frac{(a/\text{AU})^{\frac{3}{2}}}{(M/M_{\odot})^{\frac{1}{2}}} \text{days} \quad (8)$$

where  $a$  is the semi-major axis of the stellar orbit. With this in mind, monthly X-ray monitoring can only sample orbits around  $\sim 100 M_{\odot}$  BHs for stars at radial orbits of  $\gtrsim 1$  AU ( $1.5 \times 10^8$  km), where the probability of eclipsing is quite low. Thus, it is important to test for periodicity on much shorter timescales, especially when searching for evidence for IMBHs with  $M \gtrsim 100 M_{\odot}$ .

There have been very few reports of variation on time scales less than a few weeks. There

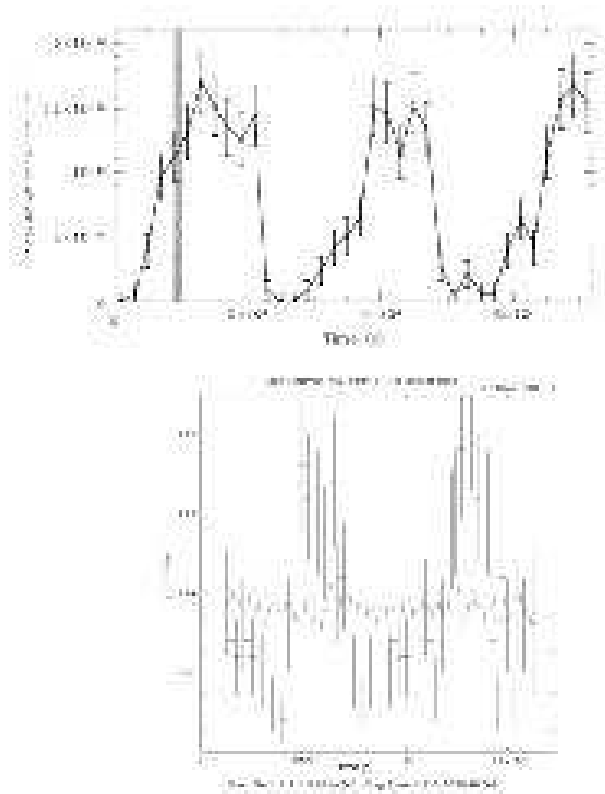


Fig. 9.— Chandra X-ray light curves of two ULXs that are candidates for periodic behavior. The upper figure shows data for Circinus Galaxy X-1 (Reprinted with permission from Bauer et al. 2002). Data for the shaded area have been interpolated. The lower figure shows variation in M51 X-7, reprinted with permission from Liu et al. (2002a). The square data points in the center show the background level.

are currently three reported cases of variability on time scales of hours, all of which have been interpreted as possibly periodic (see Figure 9). Roberts & Colbert (2003) report aperiodic variability on timescales of a few hundred seconds from NGC 6946 X-11. Bauer et al. (2001) observed one source in the Circinus galaxy to exhibit a count rate variation of a factor of 20, during a 67 ksec Chandra observation. Three peaks are seen, which are consistent with a 7.5 hour period. Bauer et al. (2001) discuss different mechanisms for this variability, including eclipses, modulation of the accretion rate, or a precessing jet. Sugiho et al. (2001) observed a ULX in the spiral galaxy IC 342 and found possible evidence for either a 31 hour or a 41 hour period, admittedly based on only two peaks. More recently, Liu et al. (2002a) and Terashima & Wilson (2003) report more than 50% variation in count rate from a ULX in M51, with a time of  $7620 \pm 500$  seconds between the two peaks seen.

It is tempting to interpret these periods as orbital periods. This would be highly constraining

for the  $\sim 2$  hour period of the M51 source, and would in fact imply that the companion is a  $\sim 0.3 M_{\odot}$  dwarf (Liu et al. 2002a). However, it is premature to draw conclusions because at this point no source has been seen to undergo more than three cycles. This is a clear case in which sustained observations, especially of the putative 2 hour period, are essential. Only then will it be possible to separate models in which the period is orbital (in which case it should be highly coherent) from models in which the period is due to, e.g., disk modes, in which the modulation could be quasi-periodic.

Variability on very short timescales (seconds to minutes) can be detected to the same level of fractional rms amplitude as variability on longer timescales, but the variability of sources from X-ray binaries to AGN tends generally to decrease with increasing frequency. This means that variability at the few percent level would be detectable out to the Nyquist frequency of observations of the brightest ULXs (e.g., to 1 Hz in the XMM data analyzed for M82 by Strohmayer & Mushotzky 2003). It would be well worth doing a systematic comparison of the broad-band power spectra of X-ray binaries, ULXs, and AGN, given that one expects the maximum frequency at which significant power exists to decrease with increasing mass. Although the lack of a fundamental theory of this variability limits our ability to draw rigorous conclusions (e.g., the stellar-mass black hole LMC X-3 has no detected variation at  $\nu > 10^{-3}$  Hz; see Nowak et al. 2001), systematic differences in the power spectra could provide insight into the nature of ULXs.

The first, and so far only, quasi-periodic oscillation (QPO) in a ULX was reported by Strohmayer & Mushotzky (2003), based on XMM observations of the brightest point source in M82. They find a QPO at 54 mHz, with a quality factor  $Q \sim 5$  and a fractional rms amplitude of 8.5%. At the time, the flux would imply a bolometric luminosity (if isotropic) of  $4 - 5 \times 10^{40}$  erg s $^{-1}$ . As discussed by Strohmayer & Mushotzky (2003), QPOs are usually thought to originate from disk emission, which if true makes this observation troublesome for a beaming interpretation. This is *not* because the frequency is low (for example, as mentioned by Strohmayer & Mushotzky 2003, a 67 mHz QPO has been observed with RXTE from GRS 1915+105, which has a dynamically measured mass of  $14 \pm 4 M_{\odot}$ ; see Morgan, Remillard, & Greiner 1997). The problem is instead that if the source is really a beamed stellar-mass black hole, the variability in the disk emission (which is nearly isotropic) would have to be of enormous amplitude to account for the observations. For example, even for a  $20 M_{\odot}$  black hole accreting at the Eddington limit, the beaming at  $4 - 5 \times 10^{40}$  erg s $^{-1}$  would need to be a factor of  $\sim 15$ , requiring intrinsic variability in the disk emission in excess of 100%. There are other sources in the XMM beam; the brightest of these sources has an equivalent peak isotropic luminosity of  $3.5 \times 10^{39}$  erg s $^{-1}$ , comparable to the luminosity in the QPO of  $3.4 \times 10^{39}$  erg s $^{-1}$  (Strohmayer & Mushotzky 2003). For this source to produce the QPO would therefore require nearly 100% modulation, which seems unlikely. These observations therefore provide indirect evidence for the IMBH scenario, although caution is still required because the theory of black hole QPOs is not settled. Recently, Cropper et al. (2003) reported that the ULX NGC 4559 X-7 has a 28 mHz break in its power density spectrum, which

is consistent with a mass of a few thousand solar masses, as is the measured thermal temperature of  $kT=0.12$  keV.

Combined spectral and temporal analyses can be a very powerful tool in diagnosing ULX emission processes. For example, “normal” BH XRBs often exhibit a soft spectrum (with power-law slope  $\Gamma \sim 2.5$ ) in their high state, and hard spectrum ( $\Gamma \sim 1.8$ ) in their low state. This type of spectral variability has also been seen from ASCA observations of several ULXs — NGC 1313 X-1 (Colbert & Mushotzky 1999), and two objects in IC 342 (Kubota et al. 2001; see also Mizuno et al. (2001)). Some ULXs observed with Chandra also show this behavior. However, the opposite type of spectral variability (high/hard and low/soft) is also seen, such as for NGC 5204 X-1 (Roberts et al. 2002a), and for four sources in “the Antennae” (Fabbiano et al. 2003). Such “anomalous” spectral variability has also been observed in some micro-quasars (e.g. GRS 1758-258, Miller et al. 2002a). Further spectral variability studies will certainly be useful for understanding the ULX puzzle.

## 2.8. Multiwavelength associations

Since many starburst galaxies have ULXs, it is natural to search for clues to how ULXs are formed and fueled by studying their environment, and searching for emission from possible companion star, accretion disk, and jet. Thus, observations of ULX fields at other wavelengths are very important. ULX environments could be young stellar clusters in starburst/spiral galaxies, or globular clusters in spiral galaxy halos and in elliptical galaxies.

The superior spatial resolution ( $\sim 1''$ ) and absolute astrometry ( $\sim 1''$ ) of Chandra has allowed matching of the positions of X-ray sources with some optical sources. For spiral galaxies, there may be an association of ULXs with star-forming regions (e.g. Matsushita et al. 2000, Roberts et al. 2002b). Young stellar clusters associated with ULXs have masses  $\sim 10^4 - 10^5 M_\odot$  (e.g., Zezas et al. 2002 for the Antennae galaxies; Matsushita et al. 2000 for M82). However, ULXs are not always directly coincident with star-forming regions (Roberts et al. 2002a, Zezas et al. 2002). Since the Antennae have so many ULXs, they can be used to determine exactly how frequently ULXs are associated with young star clusters. Zezas et al. (2002) find eight ULXs possibly associated with 18 young stellar clusters, where “associated” means separated by less than  $2''$ . By randomly scrambling the coordinates of the X-ray sources and clusters, Zezas et al. (2002) estimate that by chance there would be  $6 \pm 2$  X-ray sources associated with  $8 \pm 4$  optical sources, so the associations are still tentative. Intriguingly, Zezas et al. (2002) show that there is a small but clear separation of typically  $1-2''$  between a ULX and the nearest young stellar cluster. At the  $\approx 20$  Mpc distance of the Antennae (for  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), this corresponds to a physical distance of 100-200 pc. We will discuss in § 4 and § 5 how this separation is interpreted in different models.

The first point-like optical counterpart to a ULX was found in NGC 5204 by Roberts et al.

(2001). The optical source had a blue, featureless spectrum and an optical luminosity typical of  $\sim 8\text{--}20$  O-giant or supergiant stars. A young cluster of O giants/supergiants supports the scenario of a high-mass BH XRB. Follow-up HST imaging work by Goad et al. (2002) showed that, in addition to the luminous point source seen from the ground, there were two other fainter point sources consistent with the X-ray source. Liu et al. (2002b) found an optical counterpart to M81 X-11 with an optical luminosity and optical color of an single O-star, suggesting that the object is a high-mass BH XRB. Another point-like optical counterpart was found in HST images of a ULX in the halo of the spiral galaxy NGC 4565 (Wu et al. 2002). However, this optical counterpart appears to be a faint, blue globular cluster, and is thus inconsistent with the high-mass BH XRB scenario. HST optical spectroscopic studies of the region surrounding the nearest ULX (M33 X-8) were performed by Long et al. (2002). They do not uniquely identify the nature of the ULX, due to uncertainties in the X-ray position. This shows how complex optical follow-up work can be in crowded regions of spiral disk galaxies. Very high precision X-ray astrometry such as that of *Chandra* is needed to uniquely identify counterparts in HST images, since even for short “snapshot” exposures in optical (B, V, R, and I) bands, at least several optical sources are usually detected within an  $1''$  radius circle in disk galaxies.

In elliptical galaxies, however, the astrometry problem is not as severe. ULXs in elliptical galaxies are usually in the galaxy halo, which is sparsely distributed with optical sources (globular clusters). Thus, identification of a unique counterpart is often easier than in disk galaxies. For example, Angelini, Loewenstein, & Mushotzky (2001) performed a detailed comparison between *Chandra* X-ray sources in the giant elliptical galaxy NGC 1399 and HST counterparts, finding that 26 of the 38 sources detected at  $>3\sigma$  were obviously associated with globulars (Figure 9). Two of the three ULXs are associated with globulars. Other groups are also finding that there is a strong correlation between X-ray sources in elliptical galaxies and globular clusters (e.g. Kundu, Maccarone & Zepf 2002). It will be exciting to learn results from follow-up optical studies to determine the age, metallicity and other derivable properties for these globulars, and of other globulars with ULXs.

These results, combined with the results from starburst galaxies, show that there is a strong link between ULXs and star clusters, whether they be young star-forming regions, or globular clusters, which are 100–1000 times older. It is of interest that there are dozens of sources in globulars around NGC 1399 with  $L_X > 10^{38} \text{ erg s}^{-1}$ , given that neither our Galaxy (with  $\approx 150$  globulars, Harris 1996) nor M31 (with  $\approx 300\text{--}400$  globulars, Hodge 1992, Fusi Pecci et al. 1993) has any X-ray sources in globular clusters with  $L_X \gtrsim 10^{38} \text{ erg s}^{-1}$  (Hut et al. 1993; Supper et al. 1997). Part of this may have to do with the high number of globulars per unit mass around NGC 1399 (as it typical of elliptical galaxies), which is 15 times the average specific frequency for spiral galaxies such as the Milky Way and M31 (e.g., Kissler-Patig 1997), but there may also be evolutionary differences.

Studies of the environments around ULXs have led to some interesting results. Some examples of ULX nebulae are shown in Figure 10. Pakull & Mirioni (2002) find that the ULX in the dwarf

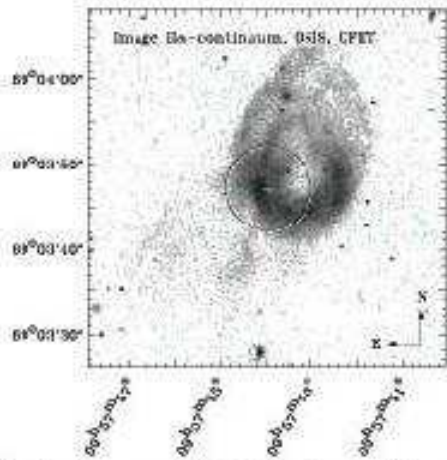


Fig. 1. Continuum subtracted H $\alpha$  image of the nebula LH9/10 around the ULX M81 X-9 (Holmberg IX X-1) shown by the error circle.

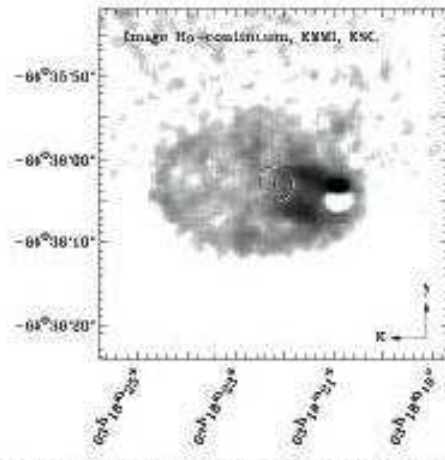


Fig. 3. The huge, 600 pc diameter H $\alpha$  bubble around the ULX NGC 1313 X-2. The nebula expands with  $80 \text{ km s}^{-1}$  and is largely shock excited.

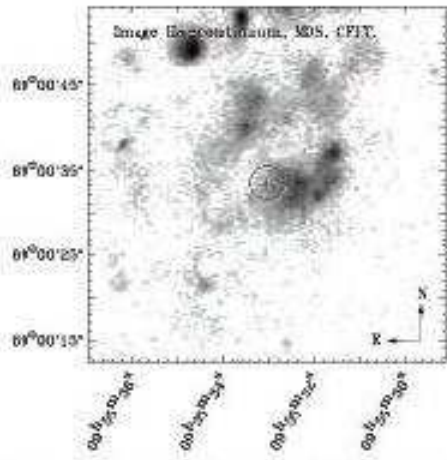


Fig. 2. H $\alpha$  image of the nebulae complex M81 23 (southern lobe) and M81 23 (northern lobe around the ULX M81 X-6, marked by the *Chandra* error circle.

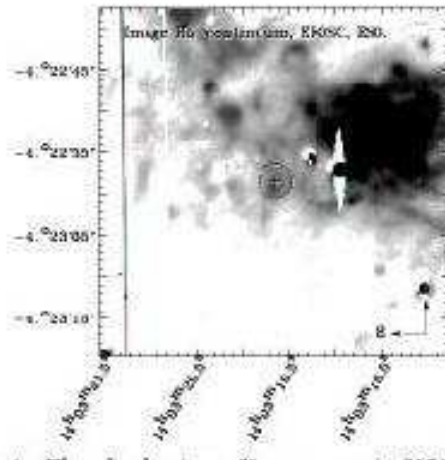


Fig. 4. The ultrasuminous X-ray source in NGC 5408 (shown by *Chandra* error circle) lies close to a giant HII region complex and is centered on a small nebula which is a non-thermal radio source.

Fig. 10.— Examples of optical emission-line nebulae near ULXs. In the top row are continuum-subtracted H $\alpha$  images of nebulae near Ho IX X-1 and NGC 1313 X-2. In the bottom row are H $\alpha$  images of nebulae near M81 X-6 and NGC 5408 X-1. Reprinted with permission from Pakull & Mirioni (2003).

galaxy Holmberg II has an optical nebula around it with substantial He II 4686Å emission. This line is produced by the recombination of fully ionized helium, which requires for its excitation a high-energy source. Since the optical luminosity is isotropic, it places a lower limit on the X-ray luminosity illuminating it; if the solid angle subtended by the nebula as seen from the X-ray source

is less than  $4\pi$  then the true X-ray luminosity is greater than inferred from the optical light, but it cannot be significantly less. Based on models of X-ray reprocessing where the X-ray source is located inside the nebula, Pakull & Mirioni (2002) conclude that the optical radiation is consistent with an isotropic X-ray source and not with significant beaming. However, there is substantial uncertainty in the correction factor from optical line flux to X-ray luminosity, so work of this type needs to be repeated for a number of sources in order to draw firmer conclusions. Integral field spectroscopic observations by Roberts et al. (2002a) indicate that many of the ULXs are actually located in cavities free from optical line-emitting gas, although it is not clear whether this is due to the absence of gas (e.g., gas cleared away by shocks), or to highly ionized gas irradiated by the ULX. Optical spectral analyses of some of these ULX nebulae show evidence for both shocks and photo-ionization (Pakull & Mirioni 2003). This is intriguing, as there are now at least two ULXs that are highly variable (and thus are accreting compact objects), but are directly associated with optical supernova remnants (IC 342 X-1, Roberts et al. 2003, and MF16 in NGC 6946, Roberts & Colbert 2003; note that the precise mechanism for the ionization is not rigorously established in these cases, and that jet ionization is a possible alternative to supernova shock ionization). Future multiwavelength studies of optical ULX nebulae and ULXs in SNRs may provide important clues as to how ULXs form, or at least how they become “active” X-ray sources.

Radio counterparts to ULXs are only just starting to be found. The first identification was reported for NGC 5408 X-1 by Kaaret et al. (2003), with an inferred 5 GHz radio power of  $\sim 10^{14}$  W Hz $^{-1}$ , consistent with relativistically beamed jet emission. If these ULXs are analogous to Galactic “micro-quasars” (XRBs with relativistic jets), which coincidentally have transverse jets, they could represent a class of “micro-blazars” that have their jets oriented directly toward the observer. Follow-up surveys are now underway to determine if relativistically beamed radio jets are common in ULXs.

### 3. Black Holes in Globular Clusters and as MACHOs

#### 3.1. Kinematics of globular clusters

As indicated in the previous section, although X-ray observations suggest the existence of black holes of masses  $M \sim 10^2 - 10^4 M_\odot$  there is as yet no direct measurement of the masses. More direct measurements might be obtained by optical observations of globular clusters. It has long been speculated (e.g., Frank & Rees 1976) that the centers of globulars may harbor  $\sim 10^3 M_\odot$  black holes. If so, the massive black holes affect the distribution function of the stars, producing velocity and density cusps. Unfortunately, observation of these cusps is difficult. For a central number density of  $10^5 - 10^6$  pc $^{-3}$ , typical of dense globulars (Pryor & Meylan 1993), the projected surface density at 10 kpc is  $\sim 10^2 - 10^3$  per square arcsecond, more than can be resolved easily with even the *Hubble* Space Telescope. Moreover, unlike the bright stars at our Galactic Center, which have been observed for a decade to provide superbly precise measurements of the central



black hole mass, the stars in globulars are old and dim.

In addition, the radius of influence of an intermediate-mass black hole is much smaller than it is for a supermassive black hole. For example, the velocity dispersion near the center of our Galaxy is  $\sim 100 \text{ km s}^{-1}$  (e.g., Tremaine et al. 2002), compared with a typical velocity dispersion of  $\sim 10 \text{ km s}^{-1}$  for a globular cluster (e.g., Pryor & Meylan 1993). The radius at which the orbital velocity around a black hole of mass  $M$  equals a velocity dispersion  $\sigma$  scales as  $M/\sigma^2$ , hence the radius of influence of the  $\sim 3 \times 10^6 M_\odot$  black hole at the Galactic center is 30 times the radius of influence of a  $\sim 10^3 M_\odot$  black hole in a globular cluster. At a distance of 10 kpc, a  $10^3 M_\odot$  black hole would influence orbits within  $\approx 1''$ , making observations very challenging but not impossible. Therefore, ground-based adaptive optics observations, along with space-based observations, have been applied to globulars to search for massive black holes.

The current evidence is promising but not yet compelling; based on *Hubble* observations, Gebhardt, Rich, & Ho (2002) report a stellar distribution in the M31 globular cluster G1 that favors the presence of a  $\approx 2 \times 10^4 M_\odot$  black hole at the  $1.5\sigma$  significance level, and van der Marel et al. (2002) and Gerssen et al. (2002) find marginal ( $0.7\sigma$ ) evidence for a  $\sim 2 - 3 \times 10^3 M_\odot$  black hole in the center of the Galactic globular M15. Given that these results require extensive and careful modeling of the stellar distributions in order to quote a significance, it is not yet possible to claim evidence for intermediate-mass black holes in these systems. Furthermore, recent n-body modeling has shown that the evidence for a black hole may be even weaker than thought previously for both M15 (Baumgardt et al. 2003a) and G1 (Baumgardt et al. 2003b). Baumgardt et al. agree that there is an excess of dark mass in the centers of these clusters, but suggest that it may be modeled well by a cluster of lower-mass objects such as white dwarfs, neutron stars, or stellar-mass black holes.

As pointed out by Gebhardt et al. (2002), van der Marel et al. (2002), and Gerssen et al. (2002), it is tantalizing that, taken at face value, the best fit masses for black holes in G1 and M15 fall directly on the extension of the relation

$$\begin{aligned} M &\approx 10^8 M_\odot (\sigma/200 \text{ km s}^{-1})^4 \\ &\approx 800 M_\odot (\sigma/10 \text{ km s}^{-1})^4 \end{aligned} \tag{9}$$

between black hole mass  $M$  and velocity dispersion  $\sigma$  found for supermassive black holes in galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001a,b; Tremaine et al. 2002; see Figure 11 for the  $M - \sigma$  relation including two possible IMBHs in globular clusters, from Gebhardt et al. 2002). Further examination of density and velocity distributions in globulars is obviously of the highest importance in understanding intermediate-mass black holes and possibly the formation of supermassive black holes.

### 3.2. Modeling of millisecond pulsar distributions

One promising path to dynamical detection of black holes in globulars involves detailed modeling of the properties of individual objects. For example, D’Amico et al. (2002) observe five millisecond pulsars in the Galactic globular NGC 6752. Three of these are in the cluster core: two of these three have negative period derivatives and one has an anomalously high positive period derivative. From this, Ferraro et al. (2003) conclude that the mass to light ratio in the core is likely to be  $M/L \approx 6 - 7$ , much higher than inferred for most globulars. If the spin derivatives are ascribed to the overall gravitational potential of the cluster, Ferraro et al. (2003) find that this implies the presence of  $1000 - 2000 M_\odot$  of underluminous matter within the inner 0.08 pc of the cluster. Possibilities for this matter include an exceptional concentration of dark remnants, a

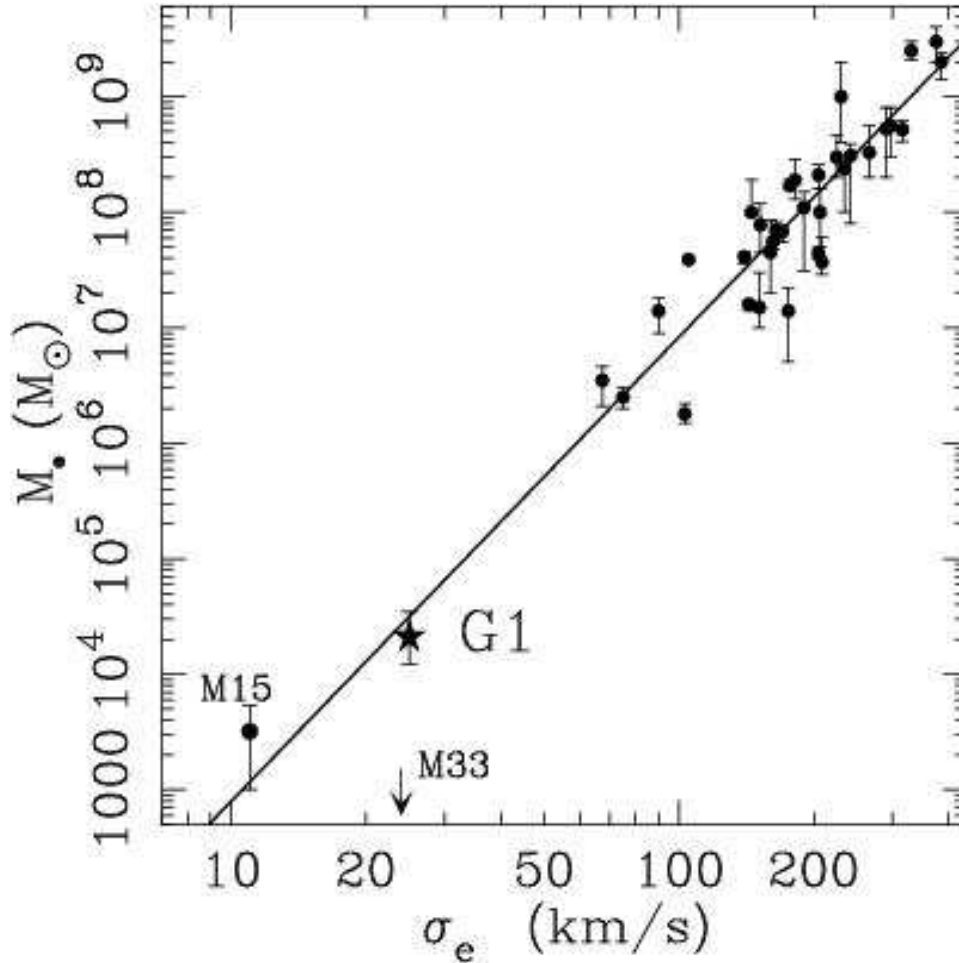


Fig. 11.— Relation between central velocity dispersion and estimated black hole masses, for a number of galaxies as well as two candidate IMBHs in globular clusters. Reprinted with permission from Gebhardt et al. (2002).

$\sim 1000 M_{\odot}$  black hole in the center of the cluster, or a  $\sim 100 M_{\odot}$  black hole that is offset but near the projected location of the three millisecond pulsars. The high spatial resolution in the Ferraro et al. (2003) observations demonstrates that there is no cusp down to 0.08 pc, implying that any central black hole has to have a mass  $M \lesssim 1000 M_{\odot}$  and be within 0.08 pc of the core.

Colpi, Possenti, & Gualandris (2002) and Colpi, Mapelli, & Possenti (2003) focus on another of the five pulsars, which is in a binary with a  $0.2 M_{\odot}$  star and is a remarkable 3.3 half mass radii away from the cluster center. After surveying various mechanisms to produce this enormous offset, they conclude that the ejection could be produced either by a black hole binary in which the black holes are large but still in the stellar range, or by an intermediate-mass black hole with a lighter companion such as a stellar-mass black hole or a collapsed star. Further monitoring will likely be necessary to understand this system better. In particular, study of the nature of the companion of the offset pulsar will help, as will additional timing studies of the core millisecond pulsars to detect or constrain the existence of wide binary companions.

### 3.3. Core rotation in globular clusters

Another potentially exciting observational development in the dynamics of globulars has to do with rotation in the core, for which a possible explanation involves an IMBH in a binary system with a stellar-mass black hole. N-body models of globulars without massive compact objects predict essentially no rotation in the cores of clusters (see, e.g., Figure 3 of Baumgardt et al. 2003b, which shows the expected rapid decrease of ellipticity inside of  $\sim 1$  pc). However, Gebhardt et al. (2000b) and Gerssen et al. (2002) find that in the center of M15 the rotational speed is comparable to the velocity dispersion,  $v_{\text{rot}}/\sigma \approx 1$  (see Figure 12, from Gerssen et al. 2002), with a correspondingly high ellipticity of isophotes (K. Gebhardt, personal communication). This might be produced if the entire cluster has a net rotation, but in M15 the position angle of the rotation in the core is different by  $100^{\circ}$  from the position angle further out, and indeed the derived position angle wanders significantly with increasing distance from the center.

As discussed in, e.g., Gebhardt et al. (2000b), typical n-body results (e.g., Einsel & Spurzem 1999) show that after an initial increase in the central rotation velocity during collapse (likely driven by the gravo-gyro instability; Hachisu 1979) the rotation velocity stabilizes, and at no point does  $v_{\text{rot}}/\sigma$  approach unity. If net rotation is introduced artificially into the core, the angular momentum is transported outwards on a timescale comparable to the core relaxation timescale, which can be  $10^7$ – $10^8$  yr for dense clusters. The central rotation may be increased in multimass models with net cluster rotation (Arabadjis & Richstone 1998), but if there is net rotation it is difficult to understand the substantial variation in position angle far from the center.

An alternative that is consistent with the data is the presence of a massive black hole binary in the core (F. Rasio, personal communication). In M15, the evidence for rotation is based on  $\sim 10$  stars in the central  $0''.5$  (Gerssen et al. 2002) with a probable total mass of  $\sim 5 M_{\odot}$ . At the

$\sim 10$  kpc distance of M15,  $0''.5$  is  $0.025$  pc. Suppose that the central mass is  $10^3 M_\odot$ . Then the total angular momentum in the central stellar system is  $L \approx 5 M_\odot \sqrt{G(10^3 M_\odot)(0.025 \text{ pc})}$ . This is the amount of angular momentum that must be deposited in the center (unless the rotation is shared by a large mass in unseen stars). A  $\sim 20 M_\odot$  black hole orbiting the  $10^3 M_\odot$  central mass at a semimajor axis  $a \sim 10^{-3}$  pc has the required angular momentum. Therefore, a  $10^3 M_\odot - 20 M_\odot$  black hole binary has enough angular momentum to account for the observed rotation. As such a

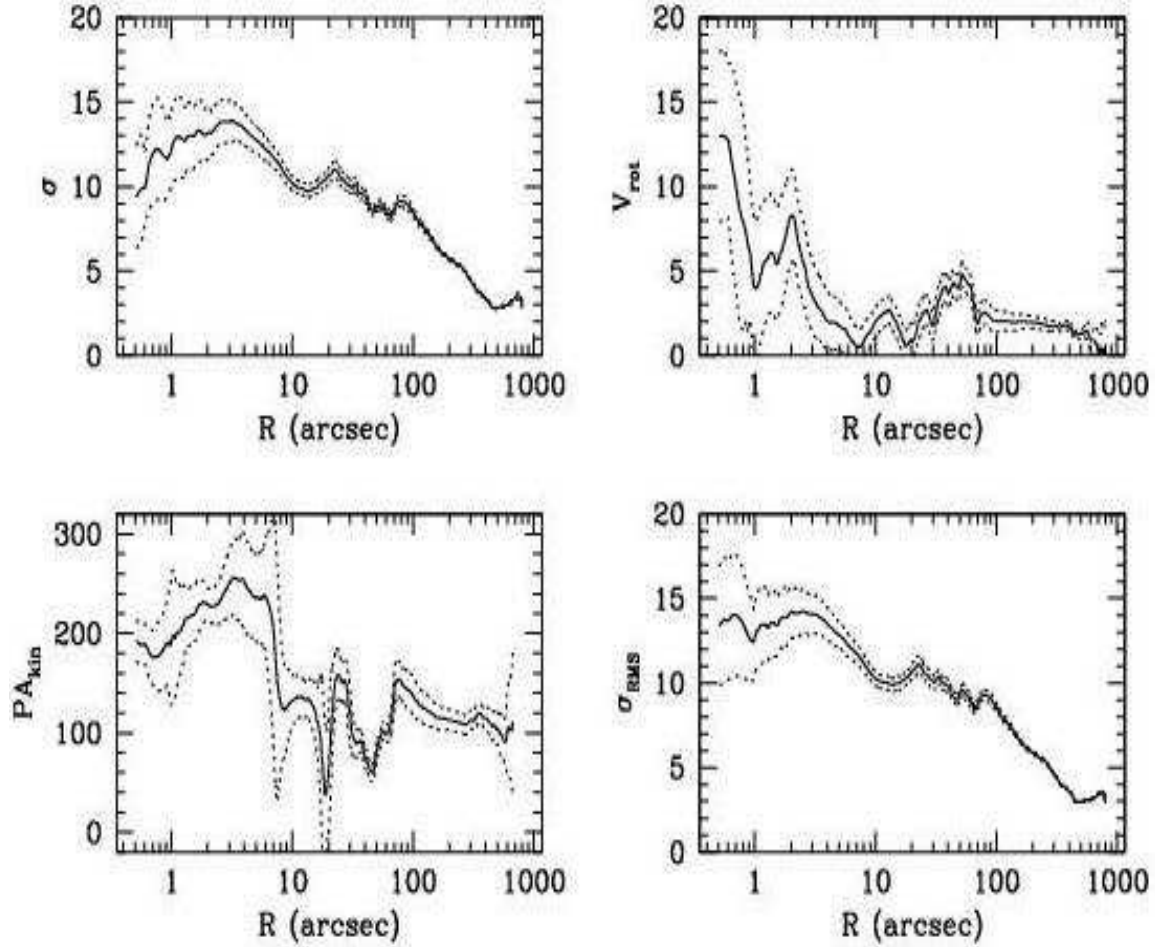


Fig. 12.— Velocity structure in the core of the Galactic globular cluster M15. Top left: random component of the line of sight velocity as a function of angular distance from the center of the cluster. Top right: systematic rotational velocity as a function of angular distance from the center. Note that  $v_{\text{rot}}/\sigma \approx 1$  near the core, indicative of significant net rotation. Bottom left: position angle of the rotation, as a function of angular distance from the center. The position angle varies significantly, suggesting that the cluster as a whole does not have a constant direction of rotation. Bottom right: total velocity dispersion, including both random and rotational components. Reprinted with permission from Gerssen et al. (2002).

binary hardens through three-body interactions, its orbital plane will change, but the net result after it becomes a tight binary is that the original angular momentum must have been transferred to the surrounding stars. Eventually, the binary will merge, then another binary will form and give its angular momentum to the stars. Successive binaries have no reason to have the same orbital planes, therefore one would expect that the position angle will vary randomly.

Note that although the original binary is much smaller than the size of the rotating region, the binary will wander by  $\sim 0.02 - 0.03$  pc for  $M \approx 10^3 M_\odot$  (Merritt 2001; see below), hence as the binary wanders it can deliver its angular momentum to the observed region. As a further consistency check, we may ask whether  $10^{-3}$  pc, or roughly 200 AU, is a reasonable size for the initial binary. If initially the massive black hole is solitary, it can capture companions by three-body exchange. If the original binary (containing a  $20 M_\odot$  black hole and a smaller companion) is hard, it has an orbital radius less than  $200(\sigma/10 \text{ km s}^{-1})^{-2}$  AU. When captured by the black hole, the binary will separate if it is larger than its Hill sphere at closest approach (i.e., if the tidal acceleration across the binary exceeds the gravitational acceleration of the binary itself). For a closest approach  $r_p$ , the critical radius is  $r_H \approx (m/3M)^{1/3} r_p$ , where  $m$  is the total mass of the binary and  $M$  is the mass of the large single black hole. For  $m \sim 20 M_\odot$  and  $M \sim 10^3 M_\odot$ , this implies  $r_p \sim 10a$ , where  $a$  is the initial semimajor axis of the binary. Therefore, the  $10^3 M_\odot - 20 M_\odot$  black hole binary can have an initial orbital radius up to  $\sim 10^{-2}$  pc, which provides plenty of angular momentum.

Analysis of other clusters is underway, with some preliminary indications that many have strong signatures of core rotation (K. Gebhardt, personal communication). If so, this is an exciting development. Not only would this provide good evidence of intermediate-mass black holes in globulars, but the rapidity with which angular momentum is transported out of the cores (in a core relaxation time, typically  $10^{7-9}$  yr) means that for us to see rotation now, there must have been a recent binary hardening event. This in turn implies that there are frequent mergers, perhaps tens to hundreds per globular in a Hubble time, and therefore these may be outstanding sources of gravitational radiation (see § 6). These data must thus be examined with special care, to make sure that there are no misleading systematics that give incorrect signatures of rotation. In addition, focused n-body modeling will be crucial to see whether there is any other way, without net rotation of the cluster, to get selective rotation of the core with a varying position angle.

### 3.4. Possible X-ray observations of IMBHs in globulars

If a  $\sim 10^2 - 10^4 M_\odot$  black hole exists in a globular, there are other possibilities for detection. Although the original component of gas in globulars is thought to have been evacuated, winds from the  $\sim 2 - 3\%$  of stars currently on the red giant branch produce a tenuous interstellar medium. Bondi-Hoyle accretion onto the central black hole can then produce visible emission in various bands, the most prominent perhaps being X-rays and radio. This accretion will happen far below the Eddington rate, and in such a regime it is difficult to predict the overall efficiency with

which luminosity is generated, due to uncertainties about the correct model of accretion in the low accretion rate limit (e.g., advection-dominated accretion flows: Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994; wind solutions: Blandford & Begelman 1999; Quataert & Gruzinov 2000). Nonetheless, one expects that a central black hole in a globular will be a faint and otherwise unidentified source. Depending on the mass of the black hole, the source may or may not be at the dynamical center of the globular. A black hole in the mass range of interest wanders around the core because of interactions with individual stars. From equation (90) of Merritt (2001), the expected wander radius of a binary black hole of total mass  $M$  in a globular cluster with a core radius  $r_c$  and field stars of mass  $m_f$  is

$$r_w \approx 0.22 \text{ pc} (20m_f/M)^{1/2} (r_c/1 \text{ pc}) . \quad (10)$$

Grindlay et al. (2001) observed the Galactic globular 47 Tuc with *Chandra* and found one unidentified X-ray source within the wander radius of a  $\sim 500 M_\odot$  black hole ( $\sim 2''$  at the 4 kpc distance of 47 Tuc) that had the right X-ray flux for Bondi-Hoyle accretion with an efficiency of  $10^{-4}$ , characteristic of low radiative efficiency flows. This is intriguing, but more than one example will be needed before conclusions can be drawn. For example, Ho, Terashima, & Okajima (2003) find only an upper limit to any X-ray emission from the dynamical center of M15.

### 3.5. Detection of IMBHs from gravitational microlensing

A final semi-direct method of detecting the masses of intermediate-mass black holes is through gravitational microlensing. Collaborations such as MACHO (Alcock et al. 2001a), OGLE (Udalski, Kubiak, & Szymanski 1997), and EROS (Afonso et al. 2003) have been monitoring the Galactic bulge and the Magellanic clouds for more than a decade, looking for the achromatic signatures of microlensing. For a fixed speed of a lens, more massive objects produce longer events because their Einstein radii are larger. The longest such events introduce a parallax signal due to the orbit of the Earth, which allows some breaking of degeneracies in the parameters of the lens.

Bennett et al. (2002a) report evidence of six events with estimated lens masses greater than  $1 M_\odot$ , with the most massive being  $6_{-3}^{+10} M_\odot$  and  $6_{-3}^{+7} M_\odot$ . Another event, detected by both the MACHO and OGLE collaborations (Bennett et al. 2002a; Mao et al. 2002), could be a  $\sim 100 M_\odot$  black hole at a distance of a few hundred parsecs, with the other interpretation being a  $\sim 3 M_\odot$  black hole in the Galactic bulge (Bennett et al. 2002b). The difficulty in being certain about the mass is that even with parallax effects there are still degeneracies between lens mass and lens distance that require modeling of the stellar distribution to make likelihood estimates. For a given event, the lens mass depends inversely on the lens distance, so there are large differences in the expected Bondi-Hoyle accretion luminosity that may be resolved with radio or X-ray observations. In the meantime, it is interesting that these same microlensing observations have placed strong limits on the fraction of halo matter that can take the form of  $1 - 30 M_\odot$  black holes (Alcock et al. 2001b).

#### 4. Formation Mechanisms for Intermediate-Mass Black Holes

Black holes in the  $10^2 - 10^4 M_\odot$  mass range are more massive than the most massive stars that are forming in the current universe, although there is uncertainty about the upper limit to current stellar masses. General considerations of radiation forces on dust grains suggest that past some mass, accretion will be suppressed (e.g., Larson & Starrfield 1971; Khan 1974; Wolfire & Cassinelli 1986, 1987; Jijina & Adams 1996). However, turbulent motion in the accreting gas can increase the limiting mass significantly (McKee & Tan 2003), and disk accretion could circumvent many of the radiation force constraints (M. Wolfire, personal communication). Observationally, the Pistol Star may have had an initial mass  $\sim 200 M_\odot$  (Figer et al. 1998), and the most luminous stars in NGC 604 could be well in excess of  $120 M_\odot$  (Bruhweiler, Miskey, & Neubig 2003). Nonetheless, current thinking suggests that stars more massive than  $\sim 200 M_\odot$  are unlikely to form in the current universe, and even if they do then mass losses to winds and pulsations will reduce the mass of any remnant black holes significantly (e.g., Fryer 1999). Therefore, if IMBHs exist they probably did not form recently from core collapse. They either formed at some earlier time, or have accumulated most of their mass since birth, or both. The primary formation mechanisms are summarized in Figure 13. In this section we review some of the proposed mechanisms, in roughly decreasing order of redshift. For a brief summary of formation mechanisms, see also van der Marel (2003) and Miller (2003).

##### 4.1. Black holes in the very early universe

An exotic possibility is that some class of black holes formed prior to big bang nucleosynthesis. This has been explored as a way to lock up a significant amount of matter in a non-baryonic form. For example, during the QCD phase transition from quark matter to nucleonic matter the equation of state of the universe was relatively soft, and hence collapse may have proceeded with relative ease (Jedamzik 1997, 1998; Niemeyer & Jedamzik 1999). However, at this phase the horizon mass (i.e., the mass of causally connected patches of the universe) was thought to be in the  $\sim 1 M_\odot$  range rather than  $10^2 - 10^4 M_\odot$  (Jedamzik 1997, 1998; Niemeyer & Jedamzik 1999), and since the horizon mass increases with decreasing redshift, the intermediate-mass black hole range would imply a transition at uncomfortably low energies. In addition, the QCD black hole formation mechanism has been criticized because it would require a perturbation spectrum that is strongly peaked and finely tuned, in order to avoid constraints based on Hawking radiation (Schwarz, Schmid, & Widerin 1999). This is therefore not the most likely mechanism, but given our lack of knowledge of this phase of the evolution of the universe, it bears keeping in mind.

#### 4.2. Population III stars

A more promising early-universe origin for massive black holes is the first generation of stars. By definition, the so-called Population III stars evolved in an environment with negligible metallicity, which in practice appears to mean a metal fraction  $Z \lesssim 10^{-5} Z_{\odot}$  (e.g., Abel et al. 1998; Bromm, Coppi, & Larson 1999; Bromm et al. 2001; Abel, Bryan, & Norman 2000; Schneider et al. 2002; Nakamura & Umemura 2002). In such an environment, metal line cooling is absent and hence the temperature of molecular clouds was higher than it is in the current universe. The Jeans mass scales as  $T^{3/2}$ , hence this suggests that the fragmentation mass and thus the initial mass of stars may be significantly larger for Population III stars than it is currently. Moreover, a zero-metallicity star has insignificant winds and weak pulsations (e.g., Fryer, Woosley, & Heger 2001), so it loses comparatively little of its mass during its evolution. A star with an initial mass

#### Formation of black hole of mass $M=100\text{--}10,000 M_{\text{sun}}$

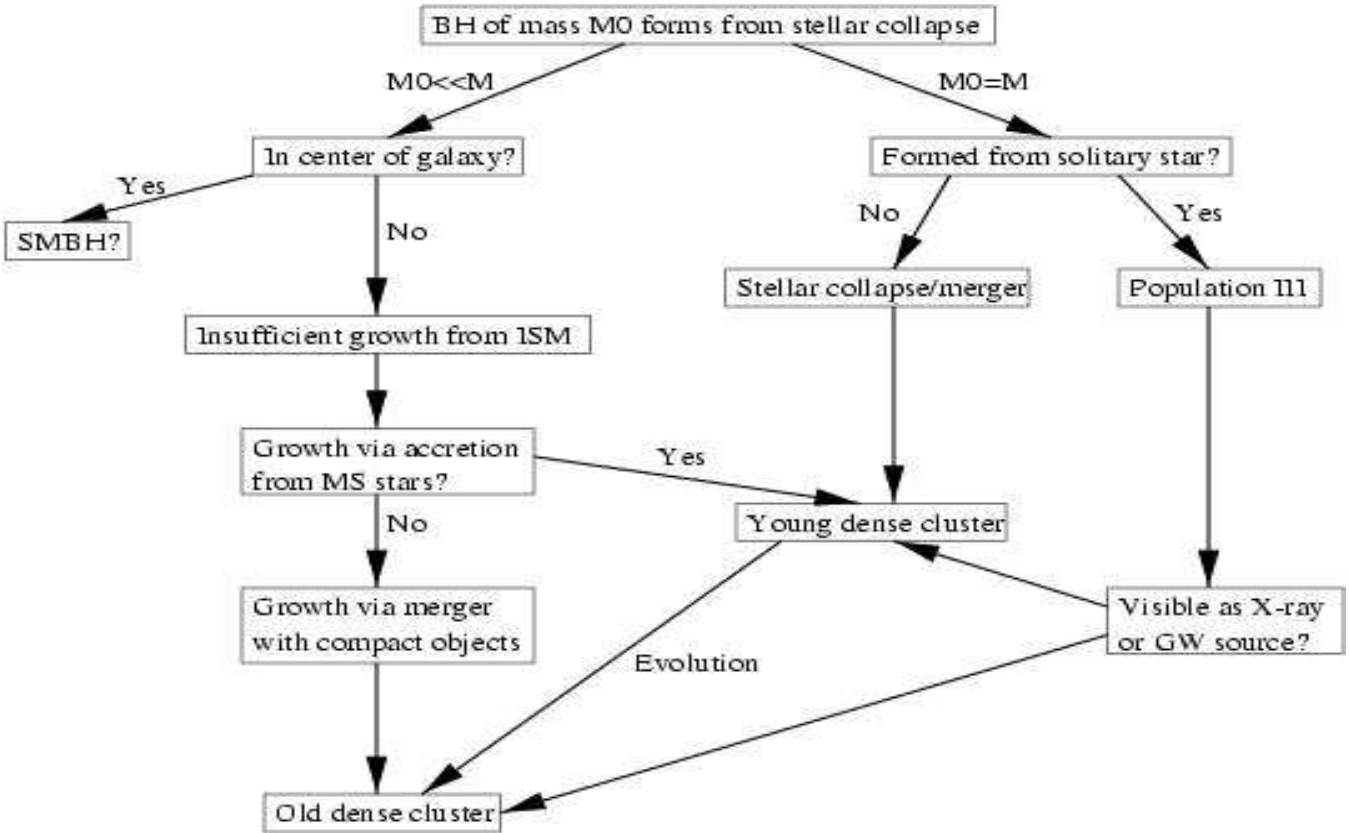


Fig. 13.— Summary of primary proposals for the formation of intermediate-mass black holes. See text for details.



between  $100 M_{\odot}$  and  $250 M_{\odot}$  is believed to disrupt itself completely via a pair instability that leads to explosive oxygen burning and leaves no remnant (e.g., Barkat, Rakavy, & Sack 1967; Woosley & Weaver 1982, Bond, Arnett, & Carr 1984; Carr, Bond, & Arnett 1984; Glatzel, El Eid, & Fricke 1985; Woosley 1986; Heger & Woosley 2002), but above  $250 M_{\odot}$  the star is not disrupted and instead is likely to collapse directly to a massive black hole, without an explosion.

Madau & Rees (2001) suggest that there may be  $\sim 10^3 - 10^4$  such black holes in a given galaxy. Such a population would normally be undetectable, because as isolated entities they would only be accreting from the interstellar medium, which would generate little luminosity. However, in an active star formation environment with many massive young star clusters, isolated black holes could be captured gravitationally. They would then sink to the center of the clusters, where they could acquire a stellar companion and become active as X-ray sources (see also Islam, Taylor, & Silk 2003). More about this general scenario will be discussed below, but this mechanism is a viable one for the ULXs. Madau & Rees (2001) have suggested (see also Xu & Ostriker 1994) that tens to hundreds of Population III black holes will sink to the centers of their host galaxies by dynamical friction, which may help in the assembly of supermassive black holes and could be a significant source of gravitational waves, detectable in the next decade at low frequencies by space-based detectors such as the *Laser Interferometer Space Antenna* (LISA; see, e.g., Danzmann 2000).

The lack of observational constraints on Population III stars means that there is still substantial theoretical uncertainty about the mass range of the first stars. For example, cooling is likely to be dominated by primordial  $H_2$  (Matsuda, Sato, & Takeda 1969; Yoneyama 1972; Hutchins 1976; Silk 1977; Yoshii & Sabano 1980; Carlberg 1981; Lepp & Shull 1984; Palla, Salpeter, & Stahler 1983; Yoshii & Saio 1986; Shapiro & Kang 1987; Uehara et al. 1996; Haiman, Thoul, & Loeb 1996; Nishi et al. 1998; Abel et al. 1998; Omukai & Nishi 1988; Couchman & Rees 1986; Bromm et al. 1999; Abel et al. 2000; Nakamura & Umemura 1999, 2001). If so, the temperature can only get down to a few hundred Kelvin, leading to stellar masses  $> 100 M_{\odot}$ . However, in some circumstances (such as the presence of dense shells or UV background radiation) the temperature may be lowered enough for cooling by hydrogen-deuterium molecules to become effective (Shapiro & Kang 1987; Ferrara 1998; Susa & Umemura 2000). Since HD has a nonzero permanent dipole moment (unlike  $H_2$ ), the transitional temperature is lower and hence cooling can proceed to temperatures of  $T \lesssim 100$  K, which produces stars of a few to tens of solar masses (e.g., Puy & Signore 1996; Bougleux & Galli 1997; Galli & Palla 1998; Flower et al. 2000; Nakamura & Umemura 2002). If this is common among the first generation of stars then the initial black holes might still have been more massive than are typically generated now, because of the lack of mass loss from winds and pulsations, but the masses may not reach several hundred solar masses. In addition, it is not currently clear how many zero-metallicity stars can form in a given galactic halo. If most stars initially have masses greater than  $250 M_{\odot}$  then there is little return of metals to the interstellar medium and several such stars can form in a primordial environment. If instead many stars are formed below  $250 M_{\odot}$ , then either normal supernovae (below  $100 M_{\odot}$ ) or pair instability

supernovae (between  $100 M_\odot$  and  $250 M_\odot$ ) disperse the heavy elements and rapidly raise the metal fraction above  $10^{-4} Z_\odot$ . As this is an active theoretical field, it is likely that in the next few years there will be convergence on the expected physics and many of these issues will be resolved.

### 4.3. Dynamics of stellar clusters

#### 4.3.1. Notes on Bondi accretion

Suppose a black hole with current mass  $M \sim 10^3 M_\odot$  was born with a much smaller mass. A quick calculation shows that the only way it could have grown to its current mass is if it spent a significant amount of time in a dense stellar cluster, unless it somehow spent billions of years in a supply of cool, dense gas. Generically, the mass could have been obtained via accretion from the interstellar medium, accretion from a companion star, or mergers. If the relative velocity of the gas and black hole is dominated by the thermal velocity, then accretion from the interstellar medium proceeds at the Bondi-Hoyle rate

$$\dot{M}_{BH} \approx 10^{12} M_{100}^2 \rho_{-24} T_6^{-3/2} \text{ g s}^{-1} \quad (11)$$

(Bondi & Hoyle 1944), where the black hole mass is  $M = 100 M_{100} M_\odot$ , the density of the interstellar medium is  $\rho = 10^{-24} \rho_{-24} \text{ g cm}^{-3}$ , and the temperature of the interstellar medium is  $T = 10^6 T_6 \text{ K}$ . Any additional velocity components, such as bulk velocity or turbulent velocity, decrease this rate. For the hot ISM, which comprises most of the volume of the ISM,  $T_6 \approx 1$  and  $\rho_{-24} \approx 10^{-2} - 10^{-3}$  (e.g., Vogler & Pietsch 1999), so the mass accretion rate is  $\approx 10^{9-10} M_{100}^2 \text{ g s}^{-1}$ . The e-folding time for mass increase is then  $(M/\dot{M}) \approx 2 \times 10^{17} M_{100}^{-1} \text{ yr}$  for the hot ISM. Even in a molecular cloud with  $T \approx 100 \text{ K}$ , the accretion luminosity itself will preheat the matter to  $\sim 10^4 \text{ K}$  (e.g., Maloney, Hollenbach, & Tielens 1996; compare Blaes, Warren, & Madau 1995 for accretion onto neutron stars). Thus, even if  $\rho_{-24} = 100$ , the e-folding time is  $\approx 6 \times 10^{10} M_{100}^{-1} \text{ yr}$ , much longer than a Hubble time and thousands of times longer than both the survival time of a molecular cloud and the crossing time of a cloud for a black hole, even if the black hole has a relative speed of only  $1 \text{ km s}^{-1}$ . Therefore, unless the black hole started out with a mass  $M \approx 10^3 M_\odot$ , accretion from the interstellar medium would add little to its mass. This conclusion is not necessarily valid in the centers of galaxies, where bar instabilities and other processes may tend to funnel high-density, low-temperature gas and foster growth of black holes. However, well off-center (as observed for ULXs), there is no known process that would preferentially keep black holes in an environment with low temperature and high density, as is needed to promote growth by Bondi accretion.

#### 4.3.2. *Merging and dynamics in clusters*

If instead a black hole grows by accretion from or merger with stars or compact remnants, then because the stars or remnants themselves have at most a few tens of solar masses, growth of several hundred solar masses requires many encounters. In galactic disks this has vanishing probability because of the low number density of stars. Therefore, only in a dense stellar cluster would one have the required number of objects with which the black hole could interact. If the cluster has a core relaxation time much less than the age of the universe (true for both young stellar clusters and globular clusters) then substantial dynamical evolution takes place and can assist in the growth of black holes. In this subsection we discuss general dynamical processes in clusters, and in the following two subsections we will examine specific proposals for the growth of intermediate-mass black holes in old (§ 4.3.3) or young (§ 4.3.4) star clusters.

A cluster of  $N$  stars in virial equilibrium with a crossing time  $t_{\text{cross}}$  relaxes dynamically on a timescale

$$t_{\text{rel}} = \frac{N}{8 \ln N} t_{\text{cross}} \quad (12)$$

(e.g., Binney & Tremaine 1987). Over several relaxation times there are a number of important trends of the evolution of the system. One is mass segregation: more massive objects tend to sink to the center of the cluster (on a timescale  $(m_f/M)t_{\text{rel}}$  for objects of mass  $M$ , where  $m_f$  is the average mass of a field star) while lighter objects increase their scale height. Therefore, generically, the more massive stars or remnants in a cluster will tend to be found in the core. In addition, because binaries act dynamically as a single object with the combined mass of the two stars, binaries also have a tendency to sink towards the core (e.g., Spitzer & Mathieu 1980; see Elson et al. 1998 for observational evidence of binaries in a young stellar cluster). In a very young cluster (a few tens of millions of years or younger), the most massive stars are still on the main sequence, hence one expects O and B stars to be in the center. In older clusters, these massive stars have evolved off the main sequence and it is their remnants (black holes or neutron stars) that are the most massive objects. Thus, in older clusters one expects the core to be rich in black holes, neutron stars, and binaries (see, e.g., Sigurdsson & Phinney 1995; Shara & Hurley 2001).

The presence of binaries adds crucial physics to the evolution of clusters. Close interactions between binaries and single stars or other binaries dominate the physics, hence these processes have been explored in a long line of numerical experiments (e.g., Heggie 1975; Hills 1975a,b; Hills & Fullerton 1980; Roos 1981; Fullerton & Hills 1982; Hut & Bahcall 1983; Hut 1983a,b; Hut & Inagaki 1985; McMillan 1986; Rappaport, Putney, & Verbunt 1990; Mikkola & Valtonen 1992; Heggie & Hut 1993; Sigurdsson & Phinney 1993; Quinlan 1996; Portegies Zwart & McMillan 2000). These experiments have shown that in three-body interactions of a binary system with a single object, hard binaries tend to get harder. That is, for a tight enough binary, the ultimate result of the interaction is usually that the binary tightens further. The resulting recoil adds to the kinetic energy budget of the globular, which expands the system. Such interactions are believed to play the dominant role in preventing catastrophic core collapse in globulars (originally suggested

by Heñon 1961; see Ostriker 1985 and Binney & Tremaine 1987 for discussions). Numerical experiments also show that in a close three-body encounter of unequal masses, the tendency is that the final binary is composed of the two most massive of the three original stars (e.g., Sigurdsson & Phinney 1993; Heggie, Hut, & McMillan 1996). As a result, even if a massive object is initially isolated, interactions with binaries are likely to allow it to exchange in. Thus, massive compact objects in the cores of globulars are likely to be in binaries.

Another trend evident in numerical simulations is that an individual three-body encounter can be extremely complex, with hundreds or even thousands of orbits required before the system resolves into a binary and a single star. During these many orbits, a pair of stars can come extremely close to each other. Newtonian simulations of three identical point masses show (e.g., Hut 1984; McMillan 1986; Sigurdsson & Phinney 1993) that the probability that the closest encounter between two stars is  $\epsilon a$  or less (for initial semimajor axis  $a$ ) during a binary-single interaction scales as  $\epsilon^{1/2}$ . Therefore, in a significant fraction of encounters, two main-sequence stars in a young cluster may come close enough to collide (Portegies Zwart & McMillan 2002; see § 4.3.4 below), or two black holes in an old cluster may come close enough that gravitational radiation is significant.

Finally, note that the large gravitational capture cross section of stellar clusters means that even if an IMBH forms independently of a young stellar cluster (as in the Population III scenario), it can be captured and sink to the core of a cluster, where it will form a bright X-ray source if the most massive stars present are still on the main sequence or giant branch. The expected number of ULXs from this mechanism is

$$N_{\text{ULX}} = n_{\text{IMBH}} N_{\text{cluster}} \sigma_{\text{cluster}} v_{\text{rel}} T, \quad (13)$$

where  $n_{\text{IMBH}}$  is the number density of IMBH,  $N_{\text{cluster}}$  is the number of super star clusters,  $\sigma_{\text{cluster}}$  is the cross section of interaction of an IMBH with a cluster,  $v_{\text{rel}}$  is the relative velocity at infinity of the IMBH, and  $T$  is the lifetime of the young cluster. For a typical super star cluster,  $M \sim 10^5 M_{\odot}$  and  $R_{\text{cluster}} \sim 10$  pc. If the IMBH has had time to settle to nearly the local standard of rest then it will have a slow speed and therefore be only weakly hyperbolic relative to the cluster. For a relative speed of  $v_{\text{rel}} = 3 \text{ km s}^{-1}$  (which equals  $3 \times 10^{-6} \text{ pc yr}^{-1}$ , enough to travel 60 pc in  $2 \times 10^7 \text{ yr}$ ), the interaction is gravitationally focused and therefore  $\sigma_{\text{cluster}} \approx \pi R_{\text{cluster}} (2GM/v_{\text{rel}}^2)$ , or  $\sigma_{\text{cluster}} \approx 3 \times 10^3 \text{ pc}^2$  for the chosen numbers.

We now need to determine whether interaction with the cluster will remove enough energy from the IMBH to make it bound to the cluster. From the Chandrasekhar formula for dynamical friction (e.g., equation 7-18 from Binney and Tremaine),

$$d \ln \mathbf{v}_{\mathbf{M}} / dt \approx 4\pi \ln \Lambda G^2 \rho M / v_M^3. \quad (14)$$

Here  $\mathbf{v}_{\mathbf{M}}$  is the velocity of the massive object,  $v_M$  is its magnitude,  $\rho$  is the average mass density of stars, and there is a proportionality factor involving error functions that is roughly 0.4 for a weakly hyperbolic encounters.

Assuming  $\rho = 10^5 M_\odot / [(4\pi/3)(10 \text{ pc})^3]$ ,  $M = 10^3 M_\odot$ , and  $v_M = 10 \text{ km/s}$  (because this is weakly hyperbolic), then for  $\ln \Lambda = 10$  we have  $d \ln \mathbf{v}_M / dt \approx 7 \times 10^{-16} \text{ s}^{-1}$ . Therefore, a “significant” change in velocity occurs in a time of  $t = 1/7 \times 10^{-16} \text{ s}^{-1} = 1.4 \times 10^{15} \text{ s}$ . At  $10^6 \text{ cm/s}$ , the distance traveled in that time is  $1.4 \times 10^{21} \text{ cm}$ . The diameter of the cluster is  $20 \text{ pc}$ , or  $6 \times 10^{19} \text{ cm}$ . Therefore, the fractional decrease in velocity is about 0.05. The total velocity is  $(10^2 + 3^2)^{1/2} = 10.4 \text{ km/s}$ , so a 5% change will reduce the speed below escape velocity and the IMBH will be captured by the cluster.

Now consider the specific example of M82. From the Hubble observations of O’Connell et al. (1995), there are  $\gtrsim 100$  super star clusters in the inner  $350 \text{ pc}$  of the galaxy. If there are  $N_{\text{IMBH}}$  IMBHs in the same volume, then  $n_{\text{IMBH}} \approx 5 \times 10^{-7} (N_{\text{IMBH}}/100) \text{ pc}^{-3}$ . If we consider  $T = 2 \times 10^7 \text{ yr}$ , then the expected number of ULXs by the capture mechanism is

$$\begin{aligned} N_{\text{ULX}} &\approx 5 \times 10^{-7} (N_{\text{IMBH}}/100) \text{ pc}^{-3} \times 100 \times 3 \times 10^3 \text{ pc}^2 \times 3 \times 10^{-6} \text{ pc yr}^{-1} \times 2 \times 10^7 \text{ yr} \\ &\approx 10 (N_{\text{IMBH}}/100) . \end{aligned} \quad (15)$$

If we assume the point sources in M82 (as listed in Table 1 of Matsumoto et al. 2001) have a highly absorbed spectrum, similar to the ULX, this implies there are 7 ULXs in M82, which is comparable to the expected number of IMBHs.

#### 4.3.3. Gradual dynamical formation of IMBHs in globular clusters

Three methods of forming IMBHs in globular clusters have been discussed:

1. Merging of binaries that have a  $\gtrsim 50 M_\odot$  black hole primary,
2. Capture of a stellar-mass black hole in a high-eccentricity orbit around an IMBH,
3. Tightening of a BH/BH binary by a Kozai resonance.

We now discuss these in turn.

The first mechanism involves hardening of a binary by three-body interactions, with the possibility of a merger due to gravitational radiation if the binary is tightened enough. However, the recoil kick experienced by both the binary and the interloper object is proportional to the orbital velocity of the binary (e.g., Heggie 1975), so the kicks get stronger as the binary hardens. If the kick speed of the binary exceeds the  $\sim 50 \text{ km s}^{-1}$  escape speed from the core of a typical globular (Webbink 1985) before the binary can merge via gravitational radiation, then the final merger will happen well outside the globular (Portegies Zwart & McMillan 2000). This may still be interesting for gravitational radiation (Portegies Zwart & McMillan 2000), but it would prevent substantial growth of a black hole. Indeed, Kulkarni, Hut, & McMillan (1993), Sigurdsson & Hernquist (1993), Portegies Zwart and McMillan (2002) find that three-body interactions of  $10 M_\odot$

black holes lead almost always to ejection from globulars. In a young stellar cluster, where the core has not yet contracted significantly, the escape velocity is much less, and ejection is virtually inevitable.

If, however, the initial mass of the black hole is somewhat larger than  $10 M_\odot$ , it has greater inertia and might be able to stay in the cluster long enough to grow significantly. Miller & Hamilton (2002a; see also Taniguchi et al. 2000) show that black holes of initial mass  $M \gtrsim 50 M_\odot$  that interact with objects of typical mass  $M < 10 M_\odot$  have enough inertia that they merge by gravitational radiation before ejection. They can, therefore, grow in a dense cluster. This process takes billions of years, and thus is not efficient enough to form a black hole in a young stellar cluster. Many interactions are required to harden a black hole binary to the point of merger, and a significant fraction of these may eject the interloper stars, depleting the supply of mass. It is therefore important to evaluate how inefficient this process is, which will allow an estimate of the maximum mass of a black hole that can be grown this way. Initial studies suggest that the high eccentricities attained during three-body interactions allow merger by gravitational radiation when the binary still has a relatively large separation, and hence the number of black holes kicked out during the hardening process may be much smaller than estimated previously (Gültekin, Miller, & Hamilton 2003).

A second possibility, which could be more efficient for black holes of mass  $M > 10^3 M_\odot$ , is direct capture by emission of gravitational radiation. If two black holes, initially unbound with respect to each other, pass close enough in a hyperbolic encounter, then emission of gravitational radiation during the encounter may take away enough energy that the holes become bound. From Quinlan & Shapiro (1989), the effective capture cross section of a compact object of mass  $m$  by a large black hole of mass  $M \gg m$  in such a plunge is

$$\begin{aligned} \sigma &= 2\pi \left( \frac{85\pi}{6\sqrt{2}} \right)^{2/7} \frac{G^2 m^{2/7} M^{12/7}}{c^{10/7} v_\infty^{18/7}} \\ &\approx 3 \times 10^{28} m_{10}^{2/7} M_{1000}^{12/7} v_6^{-18/7} \text{ cm}^2, \end{aligned} \quad (16)$$

where  $v_\infty = 10^6 v_6 \text{ cm s}^{-1}$  is the relative velocity at infinity. In cores with main sequence velocity dispersions  $v_{\text{ms}} \approx 10^6 \text{ cm s}^{-1}$  and number densities  $n = 10^6 n_6 \text{ pc}^{-3}$ , the rate of such captures is  $\nu \approx 10^{-6} n_6 m_{10}^{11/7} M_{1000}^{12/7} \text{ yr}^{-1}$  (Miller 2002). This can be competitive with the rate of three-body encounters for large  $M$ , and can dominate the capture rate because a single two-body encounter results in a merger, whereas many three-body encounters are required to harden the binary to the point of merger (Miller & Hamilton 2002a). It is therefore possible that the efficiency of black hole growth (defined as the change in mass of the large black hole divided by the mass ejected) may increase as the mass goes up.

The third channel for growth of an IMBH in a globular cluster has recently been considered by Miller & Hamilton (2002b), with consequences for gravitational radiation discussed by Wen (2002). A Newtonian binary-single interaction of point masses cannot result in a stable hierarchical triple. However, a binary-binary interaction can, and the sparse numerical results for this process suggest that a hierarchical triple results from some 20-50% of strong binary-binary interactions (e.g.,

Mikkola 1984; McMillan, Hut, & Makino 1991; Rasio, McMillan, & Hut 1995; Bacon, Sigurdsson, & Davies 1996; Aarseth 2001). If the resulting triple has a large inclination between the orbit of the outer tertiary and the inner binary, then over many orbital periods the eccentricity and inclination of the inner binary undergo a slow oscillation called a Kozai resonance (Kozai 1962; Harrington 1968, 1974; Lidov & Ziglin 1976; Innanen et al. 1997; see Ford, Kozinsky, & Rasio 2000 and Blaes, Lee, & Socrates 2002 [which corrects an error in Ford et al. 2000] for treatments to octupolar order). To lowest order, the net result of the Kozai resonance is to change the eccentricity cyclicly from its initial value to some potentially high value and back again, without changing the semimajor axis of the inner binary. If the maximum eccentricity is sufficiently close to unity, gravitational radiation can become important. Miller & Hamilton (2002b) show that, even when including post-Newtonian precession (which decreases the maximum eccentricity), this process can often lead to merger by gravitational radiation. Since this does not produce any dynamical recoil, it may be a way to build up massive black holes without ejections. Given that even a single  $50 M_{\odot}$  black hole can grow while staying in a cluster, from three-body interactions, any path to their formation has potentially important consequences.

There is, however, a possibility that even in Kozai mergers there can be a significant kick. The gravitational radiation emitted during the inspiral of two black holes is not completely symmetric, because during one period of revolution the orbit evolves. Gravitational radiation therefore carries away linear momentum, which imparts some velocity to the black holes (Peres 1962; Bekenstein 1973; Fitchett 1983; Fitchett & Detweiler 1984; Redmount & Rees 1989; Wiseman 1992). If this velocity exceeds  $\sim 50 \text{ km s}^{-1}$ , the merged system escapes from the globular. The kick velocity depends strongly on the radius of marginal stability ( $v \sim a_{ISCO}^{-4}$ ; Fitchett 1983) and also on the mass ratio (by symmetry, the kick vanishes for equal-mass nonrotating black holes; for Schwarzschild holes the kick peaks at a mass ratio of 2.6; Fitchett 1983; Wiseman 1992). The most recent post-Newtonian calculations suggest that the kick speed is likely to be well below  $50 \text{ km s}^{-1}$  (Wiseman 1992), so this will not eject black holes from clusters. However, these calculations only address the inspiral portion of coalescence, up to the innermost stable circular orbit. Current numerical and analytic calculations suggest that some 1-3% of the mass-energy of the system may be released in the final merger and ringdown (Buonanno & Damour 2000; Buonanno 2002; Baker et al. 2002), so it will be important to determine whether this phase produces substantial asymmetry in radiation and thus may eject black holes.

#### 4.3.4. *Rapid dynamical formation of IMBHs in young clusters*

In old clusters the most massive objects are stellar remnants. In contrast, the most massive objects in clusters with ages  $\lesssim \text{few} \times 10^7 \text{ yr}$  are stars on the main sequence. These will sink to the center of a cluster and perhaps decouple via the Spitzer instability (Spitzer 1969), leading to a core collapse among only the most massive stars. The resulting high number density of massive main sequence stars, combined with their large physical cross section, suggests that direct collisions

may be frequent. If multiple such collisions occur for a given object, a star with several hundred solar masses could be produced (Begelman & Rees 1978). Ebisuzaki et al. (2001), Portegies Zwart & McMillan (2002), and Gürkan, Freitag, & Rasio (2003) have suggested that this process can ultimately lead to the production of black holes of masses  $M \gtrsim 10^2 M_\odot$  in dense young stellar clusters, explaining naturally the association of ULXs with star-forming regions in spiral galaxies. A similar process has been considered by Mouri & Taniguchi (2002b), and for a dense group of black holes within a stellar cluster by Mouri & Taniguchi (2002a).

There are a number of detailed questions with bearing on the domain of applicability of this model. The first has to do with time scales. If the massive stars evolve off the main sequence before mass segregation is effective, then the resulting mass loss in supernovae is enough to decrease the central binding energy (and hence the central number density) significantly, preventing rapid mergers (Portegies Zwart et al. 1999). In addition, the remnants would be neutron stars or black holes and would thus have negligible collision cross sections. Portegies Zwart & McMillan (2002) estimate that if the half-mass relaxation time of a young cluster is less than 25 million years, core collapse can occur and there can be runaway growth of a central supermassive star. If the relaxation time is longer, mass loss from massive stars prevents core collapse. However, even relaxation times greater than 25 million years may lead to core collapse if the initial star formation tends to place more massive stars near the center of the cluster (for observations see Hillenbrand 1997; Hillenbrand & Hartmann 1998; Kontizas et al. 1998; Sirianni et al. 2002, and for a theoretical perspective see Larson 1982; Bonnell et al. 2001). Even without pre-segregation of this type, young clusters are known with central densities that may be high enough for rapid core collapse; one example is R136 in the Large Magellanic cloud (Massey & Hunter 1998).

The second question relates to the role of binaries. In globular clusters, formal core collapse (i.e., production of an infinite-density cusp at the center) is prevented by the interactions of binaries. The processes discussed earlier in this section tend to tighten hard binaries, and if the recoil speed is less than the escape speed from the cluster, the result is injection of energy into the cluster, which tends to reduce the central density. Observations of young stars suggest that a large fraction of them, particularly the high-mass stars, are in binaries. Therefore, one possible outcome is that as the young binaries sink to the center of the cluster, their interactions prevent the formation of a high-density cusp, which then prevents multiple collisions and the generation of a supermassive star. However, as pointed out by Hut & Inagaki (1985), McMillan (1986), and other authors, binary-single encounters of main sequence stars tend to promote collisions because of resonant interactions. If binaries dominate the stellar fraction in the core, binary-binary interactions can be especially important, and from Bacon et al. (1996), the probability of a close approach is even larger than it is for binary-single interactions (the numerical techniques used in this paper actually underestimated the cross sections for  $r_{\min}/a < 0.01$ , but other results should be accurate [S. Sigurdsson, personal communication]). There are therefore competing effects, between the tendency to heat the center and the increased probability of collision in a single interaction. Current simulations (Portegies & Zwart 2002) do not include primordial binaries, because of



computational limitations (although progress is being made; see Hurley, Tout, and Pols 2002; Hurley and Shara 2002; Hut et al. 2003; Aarseth 2003), but further investigation is underway to determine the regimes of parameter space in which each of these effects is most important.

The third question is what happens when two stars collide. For the low-velocity encounters expected in the center of a young cluster, numerous studies have shown that a head-on collision is well-approximated by a complete merger, with a loss of at most a few percent of the total mass (e.g., Lai, Rasio, & Shapiro 1993; Rasio & Shapiro 1994, 1995). However, the majority of collisions will not be head-on. There is thus likely to be a tremendous amount of angular momentum in the merger product. Moreover, since the stars were originally stably stratified against convection and little entropy is likely to be generated in the collision (because the collision velocity is much less than the sound speed in almost all of the star), convection is not likely to transport this angular momentum efficiently (Lombardi, Rasio, & Shapiro 1996; F. Rasio, personal communication). Other mechanisms, such as the magnetorotational instability (Balbus & Hawley 1991), are required to dispose of the excess angular momentum. There is, for example, the possibility that for a significant time an expanding disk may exist around this system, with consequences for further collisions and mass accretion that are difficult to predict. Further research is necessary. It may be that, since subsequent collisions probably occur at random encounter angles, the overall angular momentum of the system is typically small after many mergers and one can return to a “sticky particle” approximation.

Finally, assuming a collision leads to merger and production of a higher-mass star, there is the question of how much mass is lost in the form of winds and pulsational instabilities between collisions. Portegies Zwart et al. (1999) find that although wind loss slows down the rate of growth of supermassive stars it does not halt the growth entirely. At stellar masses  $M \gtrsim 100 M_{\odot}$ , there is much uncertainty about the relevant physical processes. Mass ejection from pulsations may limit the growth of stars here, or other instabilities such as pair-production supernovae (Barkat et al. 1967) may place limits at higher masses. Current work suggests that mass loss on the main sequence is unimportant, but that post main sequence mass loss might expand the core significantly in some circumstances (e.g., Gürkan, Freitag, & Rasio 2003, in preparation). Understanding of these processes will indicate how massive a black hole can arise from main-sequence stellar collisions.

Monte Carlo analyses of young clusters seem promising as a way to include most of the relevant physics without the computational limits imposed by direct N-body integration; some initial results are reported by Gürkan et al. (2003). Even if the maximum mass turns out to be much less than the masses of ULX sources or IMBH candidates in globulars, it is possible that an initial  $100 M_{\odot}$  black hole formed in this manner is a good seed for further growth by accretion of stars or, later, by mergers with compact remnants.

## 5. Alternate Explanations for ULXs

The simplest arguments that ULXs are intermediate-mass black holes are that their X-ray flux implies an isotropic luminosity well beyond the Eddington luminosity of a  $10 M_\odot$  black hole, and that their off-center locations in galaxies imply  $M < 10^6 M_\odot$  from dynamical friction arguments. However, it is essential to recognize that we currently have no *direct* measurements of the masses of the black holes in ULXs. As a result, we are forced to rely on indirect observations and even more indirect theoretical arguments to estimate the mass. These are subject to significant error. It is therefore important to examine alternatives to these models, as well as the arguments that have been raised against intermediate-mass black holes as the engines of ULXs.

### 5.1. Beaming

The most prominent alternative model has been a beaming model, in which the source is a standard stellar-mass black hole with a jet or relativistic beaming, which produces a flux in our direction that is far in excess of the average flux and thus yields a misleading estimate of the isotropic luminosity. This idea was first proposed for ULXs by Reynolds et al. (1997), and has recently been developed more extensively by King et al. (2001), Markoff, Falcke, & Fender (2001), King (2002), and King & Puchnarewicz (2002). Koerding et al. (2001) use population synthesis models for X-ray binaries to discuss the statistical aspects of beaming models. Butt, Romero, & Torres (2003) consider possible links between ULXs, microblazars, and EGRET sources, and Foschini et al. (2003) list ULXs with power law spectra that may be compatible with beamed emission.

The basic idea is simple: in many black hole sources, including the microquasars and many AGN, there is known to be beaming, which may or may not be relativistic depending on the source. Indeed, jets are also known in other sources with accretion disks, such as protostellar systems. If we are in the beam of the jet, the flux can be far beyond the average flux, either because of relativistic effects or simply because of geometrical collimation. For example, Sikora (1981), Madau (1988), and Misra & Sriram (2003) have examined beaming from a geometrically thick “funnel” configuration, and found that the flux along the axis of symmetry can be enhanced by a factor of tens compared to the isotropic Eddington flux, depending on the opening angle of the funnel and the height of its walls. There is also some geometric flux enhancement expected in warped disk models, but this is more modest (Maloney, Begelman, & Pringle 1996; Pringle 1997). Observationally, evidence for such beaming may exist for some X-ray binaries: in their review of black hole binaries, McClintock & Remillard (2003) exhibit several sources with fluxes that correspond to isotropic luminosities of  $\text{few} \times 10^{39} \text{ erg s}^{-1}$ . The distances to these sources are difficult to ascertain with precision, but combining the estimated luminosities with estimated masses of the black holes indicate fluxes that can be a few times the Eddington flux at the best derived distance (McClintock & Remillard 2003).

With such enhancement, the ULXs could be explained straightforwardly by such beaming even if the black hole itself only has  $M \sim 10 M_\odot$ . King et al. (2001) propose that the ULXs in spiral galaxies are beamed sources involving high-mass X-ray binaries during a phase of thermal timescale mass transfer, and King (2002) suggests that the ULXs in elliptical galaxies are low-mass X-ray binaries that are microquasars with their beam towards us (for a recent review of the relevant physics of accreting compact binaries, including an application to ULXs, see King 2003). King (2003) suggests that an optically thick outflow may even account for the low temperatures reported from some XMM and Chandra observations, but analysis also has to be done of whether this would imply relativistic outflows. For ULXs with fluxes corresponding to an isotropic luminosity of less than  $10^{40} \text{ erg s}^{-1}$ , the beaming factors required are only a factor of a few. For the most luminous ULXs, at  $\sim 10^{41} \text{ erg s}^{-1}$ , a  $10 M_\odot$  black hole would have to have emission beamed by a factor of  $\approx 70$  to explain the flux while remaining below the Eddington luminosity.

Beaming models have many advantages. They explain the overall flux, they are based on known source populations, and in spiral galaxies they explain the association with star-forming regions. However, there are a number of challenges to such models. For example, stellar-mass black hole candidates such as Cyg X-1 have power spectra that display significant variability up to  $\sim 100 \text{ Hz}$  (e.g., Revnivtsev, Gilfanov, & Churazov 2000). In contrast, ULXs have thus far not shown any rapid variability. Strohmayer & Mushotzky (2003) find no variability above the Poisson level at frequencies greater than  $\approx 0.1 \text{ Hz}$ , despite being able to detect variability up to  $1 \text{ Hz}$ . If the beaming is relativistic, this would increase the frequencies even more. For the thermal timescale mass transfer suggested by King et al. (2001), the mass transfer rate is well above Eddington, which might have been expected to produce rapid transient obscuration of the source (although without detailed models it is difficult to say this with certainty). As discussed in § 2.7, it is especially difficult in the beaming model to explain the 8.5% rms QPO observed by Strohmayer & Mushotzky (2003) from an M82 ULX, because QPOs are thought to be a disk phenomenon and in the beaming model the disk emission would make up only a few percent of the total observed emission.

In addition, beamed black hole sources such as microquasars or blazars often show relativistic outflow (e.g., the superluminal motion from GRS 1915+105 detected in the radio by Mirabel & Rodriguez 1994). This may be a consequence of super-Eddington fluxes caused by beaming, but the theoretical basis for relativistic outflows is not sufficiently well understood to make clear predictions. Observationally, relativistic beaming translates into an extremely flat  $\nu F_\nu$  spectrum for blazars; the typical  $\nu F_\nu$  ratio of X-rays to  $\sim 1 - 10 \text{ GHz}$  radio waves is 10-1000 for blazars (Fossati et al. 1998). In contrast, the few ULXs that have been studied in radio usually show only upper limits to radio emission, with even the detections giving X-ray to radio ratios of  $\sim 10^5 - 10^6$  (e.g., Kaaret et al. 2003; Neff et al. 2003). For black holes of stellar mass the radio cutoff frequency may be higher than it is for supermassive black holes, but there is evidence that the X-ray to optical ratio in ULXs is much larger than it is in beamed AGN as well (R. Mushotzky, presentation at “The Astrophysics of Gravitational Wave Sources”, 25 April 2003, College Park,

MD; see also Zampieri et al. 2003). Perhaps the emission mechanism is different or the different mass scale produces different spectra, but this is an observation that needs to be explained.

## 5.2. Super-Eddington emission

Even if the emission is quasi-isotropic, it could be that the luminosity is well above the Eddington limit (Watarai, Mizuno, & Mineshige 2001; Begelman 2002). Recall that, technically, the Eddington limit only applies when (1) the emission and accretion are quasi-isotropic, and (2) the dominant opacity is Thomson scattering. If magnetic fields are strong enough,  $B \gtrsim 10^{13}$  G, Thomson scattering is suppressed and hence the Eddington limit can be raised significantly, as is thought to be the case for soft gamma-ray repeaters (e.g., Thompson & Duncan 1995; Miller 1995). Even for weaker fields  $B \sim 10^{12}$  G, accretion in a column may be able to provide enough anisotropy to allow super-Eddington emission (e.g., A0535-668, see Bradt & McClintock 1983; Arons 1992 for a theoretical treatment). However, black holes have no native magnetic fields and accretion disks cannot attain the required fields, so this is not an option. During a supernova the accretion rate can be enormous, perhaps a few tenths of a solar mass in a few seconds, and this is made possible because the temperatures are great enough that neutrino emission dominates and radiation forces are small as a result. But normal accretion of a star onto a black hole misses these temperatures by three orders of magnitude, so this is also unimportant. The remaining possibility is anisotropy of accretion and/or emission.

Begelman (2002) has pursued this line of thought and has conceived of a potentially stable arrangement of matter in which radiation effects cause accreting matter to clump. These clumps are linked by weak magnetic fields. Radiation then moves primarily in the low-density medium between the clumps, and this can in principle be stable. Clumping of this type has been observed in some numerical simulations (Turner et al. 2003). It will be interesting to see this idea developed further, and in particular to determine what conditions are necessary for it to occur. It would be especially useful to know what other observational properties would distinguish such rapidly accreting black holes from ordinary sub-Eddington accretors. Recent work by Ruszkowski & Begelman (2003) suggests that the total luminosity obtainable in these systems is  $\leq 10$  times the standard Eddington limit. If further work confirms this, it means that the most luminous of the ULXs might still require higher masses than are usually considered for stellar-mass black holes.

## 5.3. Motivation for stellar-mass models of ULXs

The invocation of accreting stellar-mass black holes to explain ULXs is reasonable because it involves a known class of sources and might be able to match many of the observed properties of ultraluminous X-ray sources. In addition, there have been a number of concerns about the viability of models involving intermediate-mass black holes. Issues that have been raised include

two observational and three theoretical problems:

1. The inferred disk temperatures are too high for an IMBH.
2. The luminosity function of X-ray point sources shows no evidence for a new component.
3. IMBHs cannot evolve in a binary.
4. IMBHs cannot grow in stellar clusters.
5. Separations of ULXs from young stellar clusters are inconsistent with the IMBH model.

We now examine these issues in turn.

*ULXs have high disk temperatures, therefore low mass.*—This argument comes from the  $kT \approx 1.4 - 1.8$  keV inner disk temperatures inferred with a MCD model from ASCA data (Kotoku et al. 2000). Recalling that in standard MCD fits,  $kT \sim 1 \text{ keV} (M/10 M_\odot)^{-1/4}$ , this would imply masses of just  $1-2 M_\odot$ . Therefore, if the temperatures really are that high, it does indeed pose a problem for models in which  $M \sim 10^2 - 10^4 M_\odot$ . However, as discussed in § 2, it is not clear whether the temperatures *are* that high. None of the data collected with *Chandra* or *XMM* strongly favor a multicolor disk model over alternate spectral forms such as power laws or bremsstrahlung, even for sources for which ASCA data did favor the MCD model (Smith & Wilson 2003). In addition, there are several sources for which XMM and Chandra fits may suggest low disk temperatures of a few tenths of a keV, consistent with black hole masses in the hundreds to thousands of solar masses (e.g., Kaaret et al. 2003; Miller et al. 2003a; Miller et al. 2003b). It may be that the lack of ASCA spectral coverage below 0.5 keV and/or its relatively large point spread function introduce systematics in the fits. This is an issue that needs to be examined carefully, source by source, with *Chandra* and *XMM*. In addition, there are soft excesses in narrow line Seyfert galaxies such as Ark 564 (Turner et al. 2001) and Ton S180 (Turner et al. 2002) that would imply high “disk temperatures”, but these are clearly supermassive objects.

It is important to emphasize that continuum spectra can often be fit well by a variety of models, which have very different interpretations. With this in mind, one must exercise caution in linking spectral fits to physical inferences about a system. The recent work with *XMM* and *Chandra* demonstrates only that previous claims of high temperatures are not required, and should not be used as a strong argument for low disk temperatures and hence high black hole masses. Nonetheless, the current situation is fully consistent with the intermediate-mass black hole hypothesis.

*The luminosity function of bright point sources has a constant slope, hence a new population is excluded.*—The luminosity functions for X-ray point sources in the Antennae (Zezas & Fabbiano 2002) and NGC 4485/4490 (Roberts et al. 2002) can be fit by constant slope power laws. As mentioned by van der Marel (2003), one might expect that if a new component is introduced at

a high flux (e.g., intermediate-mass black holes) the slope would change as a result. Although potentially interesting, this argument is not currently compelling, for two reasons.

The most important is that the number of sources beyond the flux corresponding to a  $10 M_{\odot}$  black hole at the Eddington luminosity is so small that the error bars are huge. For example, although the luminosity functions from Zezas & Fabbiano (2002) and Roberts et al. (2002b) are broadly consistent with a single power law, they are also consistent with a broken power law or many other forms. For example, as stated by Zezas & Fabbiano (2002), there may be a break in the X-ray luminosity function of the Antennae around  $10^{39} \text{ erg s}^{-1}$ , although it is not statistically significant. There may be a similar turnover in the Roberts et al. (2002b) data on NGC 4485/4490 at  $\sim 10^{40} \text{ erg s}^{-1}$ , but in both cases the number of sources is far too small to draw any conclusions.

Another problem is that if this argument is valid, *any* change in the source population would be expected to change the slope in the luminosity function. For example, if at a certain flux level there is a transition to beamed sources from the quasi-isotropic emission thought to dominate the  $L < 10^{38} \text{ erg s}^{-1}$  population, then one would expect a break in the luminosity function because some fraction of the sources will be missed. Similarly, if the higher fluxes arise because of a new disk geometry that allows super-Eddington luminosities, there is no reason to expect that the power law slope will remain constant. Perhaps at some point the luminosity functions of point X-ray sources in many galaxies can be combined to make a more statistically reliable statement (for an initial analysis see Gilfanov et al. 2003), although care would be needed in selecting a uniform sample of galaxies.

*A  $M > 100 M_{\odot}$  black hole cannot evolve in a binary.*—This applies to a scenario in which a very massive star (a few hundred solar masses) in a binary with another star evolves to become an IMBH in a binary. As argued by King et al. (2001), even if a such a massive progenitor exists (which seems unlikely), Roche lobe overflow as opposed to common-envelope evolution would demand an orbital period in excess of a year. Simple irradiated-disk theory (King & Ritter 1998) may also imply long-term luminosity behavior that is inconsistent with X-ray observations (King et al. 2001). Therefore, it appears highly improbable that a binary system with an intermediate-mass black hole could have evolved in isolation in the current universe. However, as discussed in § 4, a  $\sim 10^2 - 10^4 M_{\odot}$  black hole can *capture* a stellar companion in a cluster. Pending further investigation, this therefore appears to provide a viable mechanism for the growth of IMBHs.

*A  $M > 100 M_{\odot}$  black hole cannot grow in a cluster.*—A separate argument is also discussed by King et al. (2001). They consider whether a stellar-mass black hole (some tens of solar masses) can, via repeated dynamical encounters, grow to hundreds to thousands of solar masses. Based on the simulations of Kulkarni, Hut, & McMillan (1993) and Sigurdsson & Hernquist (1993), which involve binary-single interactions of three  $10 M_{\odot}$  black holes, dynamical interactions would eject black holes, preventing growth. However, there have now been scenarios described in the literature that plausibly allow significant growth in clusters. As discussed in § 4, Ebisuzaki et al. (2001),

Portegies Zwart & McMillan (2002), and Gürkan et al. (2003) have proposed that in young stellar clusters there may be a significant number of direct stellar collisions that produce a large star and an extra massive black hole remnant after a supernova. In older clusters, Miller & Hamilton (2002a) show that a black hole with initial mass  $M \sim 50 M_\odot$  can stay and grow in a globular cluster, and that binary-binary interactions can produce mergers without substantial dynamical kicks. At this point, therefore, growth of a black hole in a dense stellar cluster is still a possibility.

Another potential concern is that asymmetric emission of gravitational waves during coalescence could produce enough momentum flux to kick black holes out of a globular or young stellar cluster. As discussed in § 4, current evidence is that this would not happen, although numerical calculations of the merger phase are needed for this to be definitive.

*A  $M > 100 M_\odot$  black hole would not be separated from its cluster.*—In their report of *Chandra* observations of ULXs in the Antennae, Zezas & Fabbiano (2002) point out that although there is an excess of young stellar clusters near the sources, the X-ray sources are usually displaced from the clusters, by a projected distance of 1-2" (corresponding to 100-200 pc at a distance of 20 Mpc [for  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ]). They argue that this rules strongly in favor of lighter black holes, based on an assumed momentum kick during a supernova that delivers a speed  $v = 245(M_{\text{tot}}/M_\odot)^{-1} \text{ km s}^{-1}$ , where  $M_{\text{tot}}$  is the mass of the black hole plus companion. At  $10 \text{ km s}^{-1}$  a star will travel 300 pc in 30 Myr, which is roughly the upper limit of the age of the young clusters, so Zezas & Fabbiano (2002) argue that the total mass can be no more than  $\sim 20 M_\odot$ . If the supernova kick is greater, e.g., the  $\sim 100 \text{ km s}^{-1}$  inferred for the  $6 M_\odot$  black hole in GRO J1655 (Mirabel et al. 2002), then the upper limit is pushed to  $\sim 60 M_\odot$ , but this is still well below the hundreds of solar masses inferred from Eddington luminosity arguments.

Higher masses are allowed if there are other sources of velocity than the initial supernova. For example, as discussed in § 4, three-body interactions are expected to deliver a substantial set of kicks. From Table 3 of Maiz-Apellaniz (2001), the typical half-light radius of a young super star cluster (similar to those in the Antennae) is 3–20 pc, which for a mass of  $10^5 M_\odot$  implies an escape velocity of 7-15  $\text{km s}^{-1}$  (young star clusters have not had as much time to concentrate the densities in their cores, which is why the escape velocity is less than that for globulars). The question is then whether three-body interactions can produce a  $\sim 10 \text{ km s}^{-1}$  kick that ejects the black holes from the clusters and produces the observed separation.

From Quinlan (1996), in a three-body interaction of an interloper of mass  $m$  with a binary of total mass  $M_{12}$ , the recoil speed of the binary after a three-body encounter is typically  $v_{\text{kick}} \approx 0.85(m/M_{12})^{3/2}$  times the binary orbital velocity  $v_{\text{bin}} = 300(a/1 \text{ AU})^{-1/2}(M_{12}/100 M_\odot)^{1/2} \text{ km s}^{-1}$ . When  $a \approx 10^{12} \text{ cm}$  for typical masses, Roche lobe overflow occurs for an early-type main-sequence star. Therefore, if the required kick is delivered for  $a > 10^{12} \text{ cm}$  it is possible to have the observed separation (larger separations will still undergo Roche lobe overflow when the companion star evolves off the main sequence). From

the above numbers, the kick velocity is

$$v_{\text{kick}} \approx 40(m/10 M_{\odot})^{3/2}(M/100 M_{\odot})^{-1}(a/10^{12} \text{ cm})^{-1/2} \text{ km s}^{-1}. \quad (17)$$

Therefore, if the most massive star typically interacting with the black hole binary has  $m = 10 M_{\odot}$ , the required speed can be attained for  $M < 400 M_{\odot}$ . If  $m = 20 M_{\odot}$ ,  $M < 1000 M_{\odot}$  is allowed. The time to dynamically evolve to this state is also consistent; from the numbers in Miller & Hamilton (2002a),  $3 \times 10^7$  yr suffices for the required orbital tightening if  $M < 300 M_{\odot}$  for  $m = 10 M_{\odot}$ , or if  $M < 1000 M_{\odot}$  for  $m = 20 M_{\odot}$ , assuming a central cluster number density of  $3 \times 10^5 \text{ pc}^{-3}$ , which is comparable to the expected density of the clusters in the Antennae (Zezas & Fabbiano 2002). The conclusion is that, whether intermediate-mass black holes are formed in young clusters or formed elsewhere, dynamical three-body kicks are consistent with the observed separation of ULXs from their presumed parent clusters.

Overall, the current state of the field is unsettled. No definitive observations exist for any single ULX, let alone the class of ULXs, that rule out intermediate-mass black holes, or beaming, or super-Eddington emission. Observations of QPOs and Fe K $\alpha$  lines such as in Strohmayer & Mushotzky (2003) may come close to ruling out beaming in individual sources, but there are still uncertainties in modeling. Only theoretical plausibility arguments exist, and the weighting of them depends on the bias of the individual researcher.

What, then, could resolve the interpretation? Fundamentally, the current disagreements exist because the crucial parameter — the mass — has not been measured observationally. Radial velocity measurements for any source would be conclusive if they yield minimum masses greater than  $100 M_{\odot}$ . If instead mass estimates of several of the brightest sources consistently produced  $M \sim 10 M_{\odot}$ , models involving stellar-mass black holes would be favored strongly. Note that one cannot make definitive statements about the entire class of ULXs, so it may be that some ULXs conform to each of the models proposed. In a slightly more model-dependent way, observation of a ULX in an elliptical galaxy would be important if the ULX is demonstrably far from any globular cluster. This is because all current IMBH models require the presence of dense stellar clusters to feed the source. An old (and therefore low-mass) star in an elliptical would not be able to feed an IMBH at the implied rates for long, therefore an observation of this kind would favor beaming interpretations. It is also possible that long-term transient behavior will distinguish between stellar-mass and more massive black holes in binaries (Kalogera et al. 2003). In § 7 we discuss other observations and theoretical calculations that will add important data. We now consider some of the implications if intermediate-mass black holes are common in the universe.



## 6. Implications of Intermediate-Mass Black Holes

### 6.1. Formation of supermassive black holes

If intermediate-mass black holes exist in abundance, then depending on how they are formed they may have important implications for the growth of black holes in the centers of galaxies. For example, as suggested by Madau & Rees (2001), if Population III stars form  $\sim 10^3 M_\odot$  black holes then some of these may sink to the centers of their host galaxies and form seeds for growth of supermassive black holes by gas accretion. It is also conceivable that some supermassive black holes may have grown primarily by coalescence of a number of intermediate-mass black holes. This may be required if some bright quasars exist at  $z > 10$ , where the age of the universe is  $\sim 5 \times 10^8$  yr, because at an Eddington mass e-folding time of  $4.4 \times 10^7 (\epsilon/0.1)$  yr, where  $\epsilon \equiv L/(\dot{M}c^2)$  is the accretion efficiency, it would take  $> 8 \times 10^8 (\epsilon/0.1)$  yr to grow from  $10 M_\odot$  to  $10^9 M_\odot$ . If the accretion is in a disk with a constant sense of rotation this can be well in excess of a billion years, because the accretion efficiency increases for prograde orbits. Coalescence of black holes is not subject to this limit, so rapid growth is possible. However, it has been pointed out by Hughes & Blandford (2002) that any supermassive black hole with substantial rotation (as inferred, e.g., from Fe K $\alpha$  line profiles or jets) cannot have accumulated its mass *primarily* by coalescence of small black holes on random trajectories, because orbits in opposite directions lead to a net small angular momentum. It may, nonetheless, be possible to speed up the process by building a  $\sim 10^6 M_\odot$  black hole by coalescences, then accreting gas to the final current mass.

If the  $M - \sigma$  relation derived for supermassive black holes in galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000a; Merritt & Ferrarese 2001a,b; Tremaine et al. 2002) also applies to globulars (Gebhardt et al. 2002; van der Marel et al. 2002; Gerssen et al. 2002), this has major consequences for the origin of the correlation. The central potentials of globulars are extremely shallow compared to those of galaxies. If, nonetheless, black hole formation mechanisms are similar, this undoubtedly is a major clue towards the origin of massive black holes, and possibly towards whether the black holes have a fundamental influence in the evolution of globulars and galaxies.

### 6.2. Gravitational radiation sources

Perhaps the most intriguing implication of intermediate-mass black holes is their potential as gravitational radiation sources. In particular, if these objects are commonly found in the centers of dense clusters, repeated interactions with other compact objects may cause them to undergo tens to hundreds of coalescences per Hubble time, many of which could be detected by ground-based or space-based gravitational wave instruments. These dynamical interactions produce relatively high eccentricities, that could produce observable signals of several post-Newtonian effects during inspiral. Finally, intermediate-mass black holes spiraling into supermassive black holes could

generate high signal to noise spectra with a large mass ratio that can be analyzed to determine the three-dimensional structure of spacetime around a rotating supermassive black hole. We now discuss each of these possibilities in turn.

*Coalescence in clusters.*—As discussed in § 4, a massive black hole in a dense cluster will sink to the center, where it is likely to acquire a binary companion in a short time (see also Benacquista 1999, 2000, 2002a,b; Benacquista, Portegies Zwart, & Rasio 2001). Repeated interactions harden the binary, leading ultimately to coalescence by gravitational radiation. The overall rate of these events and their detectability depend on a number of factors, including the fraction of star clusters that have a massive black hole, the mass distribution of black holes, the typical mass of objects that coalesce with the black holes, and the history of growth of the black holes. Here we give a brief summary of one particular scenario that illustrates many of these effects; for details see Miller (2002).

Suppose that the  $M - \sigma$  relation found for supermassive black holes in galaxies (see § 3.1) also holds for globular clusters. Then, from the number density of globulars and the distribution of their velocity dispersions, we have an estimate of the mass distribution of intermediate-mass black holes in globulars and how common they are.

A rough fit to the compilation of Pryor & Meylan (1993) yields a probability distribution for the velocity dispersion of Galactic globular clusters of

$$P(\sigma)d\sigma \approx e^{-\sigma/4.3 \text{ km s}^{-1}} (d\sigma/4.3 \text{ km s}^{-1}) . \quad (18)$$

The current average number density of globulars is  $n_{\text{GC}} \approx 8h^3 \text{ Mpc}^{-3}$ , where  $h \equiv H_0/100 \text{ km s}^{-1}$  is approximately 0.7 (Mould et al. 2000). If the comoving density of globulars has remained constant, then the locally measured density scales as  $(1+z)^3$  and the number per steradian per unit redshift is (e.g., Peebles 1993, equation 13.61):

$$\frac{dN}{dz} = n_{\text{GC}}(H_0/c)^{-3} F_n(z) \quad (19)$$

where  $H_0$  is the Hubble constant and  $F_n(z)$  is

$$F_n(z) = [H_0 a_0 r(z)]^2 / E(z) , \quad (20)$$

where for a flat universe ( $\Omega_m + \Omega_\Lambda = 1$ ),  $E(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$  and  $H_0 a_0 r(z) = \int_0^z dz/E(z)$  (e.g., Peebles 1993). For our calculations we assume  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ . Roughly half of all globulars may have been destroyed in the last  $10^{10}$  yr by interactions with their host galaxies (Gnedin & Ostriker 1997; Gnedin, Lee, & Ostriker 1999; Takahashi & Portegies Zwart 1998, 2000), so the number density at earlier epochs may have been larger. We will be conservative and not correct for this.

We now need to adopt a model for how the black holes in globular clusters are built up. Let us assume that such black holes are born with an initial mass  $M_{\text{init}}$ , and that they reach their current

masses (as given by the galactic  $M - \sigma$  relation) via accretion of compact objects of mass  $\Delta M$ . Let us also assume that this accretion occurs at a constant rate. In reality, because the effective interaction cross section of a black hole increases with its mass, it is probable that the coalescence rate increases with time. Therefore, an assumption of a constant rate should underestimate the detection rate somewhat, given that later coalescences are at lower redshift and thus will give stronger signals.

The signals themselves are usually divided into the phases of inspiral, merger, and ringdown. Inspiral is the long stage from the initial separation to the innermost stable circular orbit, merger is the coalescence of the horizons, and ringdown is the final phase in which the now single black hole settles into the Kerr spacetime. Inspiral and ringdown can be treated analytically (although the final stages of inspiral need post-Newtonian treatments), but merger can only be simulated numerically, meaning that reliable waveforms do not yet exist for this phase. The successive phases have higher and higher frequencies. For example, inspiral of a test particle into a nonrotating black hole has a highest gravitational wave frequency (twice the orbital frequency for a circular orbit), at the innermost stable circular orbit, of  $f_{\text{inspiral}} = c^3/(6^{3/2}\pi GM) \approx 4.4 \times 10^3 (M_\odot/M)$  Hz. The characteristic highest frequency for merger and ringdown is of order the light crossing time of the horizon, which is  $c^3/(GM) \approx 2 \times 10^5 (M_\odot/M)$  Hz (with a factor less than unity depending on the exact mode). Therefore, ground-based detectors (sensitive to frequencies  $\sim 10 - 10^4$  Hz) could detect merger or ringdown for most IMBH, but inspirals will be easiest to see for the lower-mass members of this class.

The results of the globular cluster model are shown in Figure 14, where the estimated rates in the inspiral, merger, and ringdown phases are displayed as a function of the mass of objects accreted, assuming an initial mass of  $10 M_\odot$  (first three panels), and as a function of the initial mass, assuming accretion of  $10 M_\odot$  compact objects (bottom right panel). For the merger and ringdown panels we show the rate as a function of accreted object mass for different efficiencies  $\epsilon$ , where for a binary of reduced mass  $\mu$  and total mass  $M$  we assume that during merger or ringdown a total energy of  $\epsilon M(4\mu/M)^2$  is released in gravitational waves. Based on the effective one-body calculations of Buonanno & Damour (2000) and Buonanno (2002), and the numerical calculations of Baker et al. (2002), we consider  $\epsilon = 0.005, 0.01$ , and  $0.02$  (from bottom to top in the two panels). In the bottom right panel we assume  $\epsilon = 0.01$ . Consistent with the estimates of Miller (2002), we find that some tens of events per year involving intermediate-mass black holes are likely to be observable with the planned advanced LIGO detector in its standard configuration, with most of those coming during the merger or ringdown phases. The noise at low frequencies is decreased by lowering the laser power and working on other non-fundamental design parameters, hence with tuning a larger number of events could be detected. Some mergers could be detected with mass ratios greater than  $\sim 40$ , which might simplify numerical treatment.

*Long-term inspiral of black holes into IMBH.*—Whereas the signals detected with ground-based interferometers will be during the end of inspiral or later, space-based detectors such as the *Laser Interferometer Space Antenna* (LISA) are sensitive to lower frequencies,  $\sim 10^{-4} - 1$  Hz, and

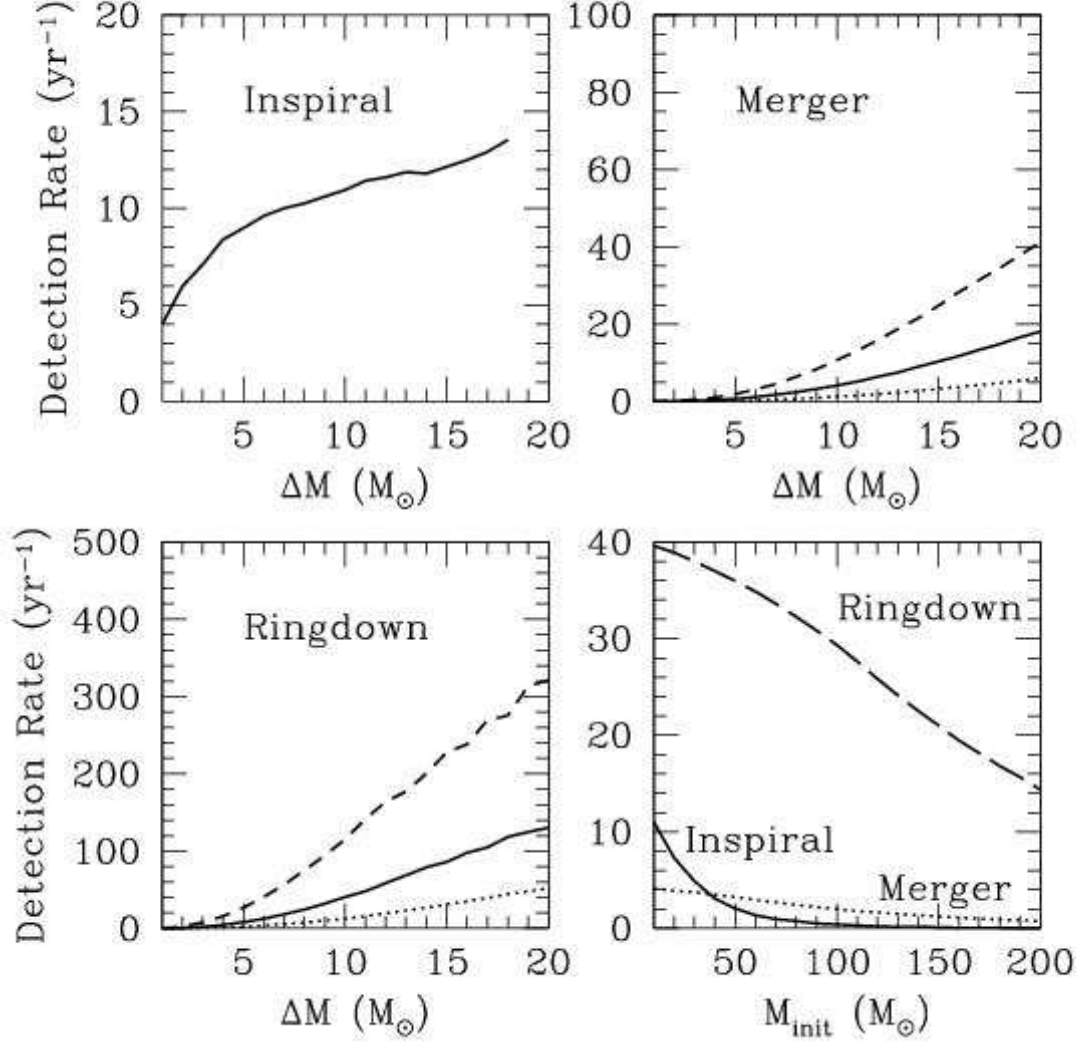


Fig. 14.— Estimated rates of detection with the advanced LIGO detector (in its standard configuration) of stellar-mass compact objects falling into intermediate-mass black holes. The overall model, of black holes in globular clusters growing by mergers, is described in detail in the text. Top left: estimated detection rate from the inspiral phase, as a function of the mass of objects merging with the intermediate-mass black hole. In this and the next two panels, the initial mass of the black hole is assumed to be  $10 M_{\odot}$ . Top right: estimated detection rate from the merger phase, as a function of the mass of merging objects. From bottom to top, the curves assume an energy release during merger of  $0.005(4\mu/M)^2 M$ ,  $0.01(4\mu/M)^2 M$ , and  $0.02(4\mu/M)^2 M$ , where  $M$  is the total mass of the binary and  $\mu$  is the reduced mass. Bottom left: estimated detection rate from the ringdown phase, as a function of the mass of the merging objects. Curves are the same efficiencies as in the top right panel. Bottom right: detection rates in the inspiral, merger, and ringdown phases as a function of the initial mass of the black hole, assuming merger with  $10 M_{\odot}$  objects. Here we assume energy releases of  $0.01(4\mu/M)^2 M$  for both the merger and ringdown phases.

hence will observe the longer-term inspiral of stellar-mass compact objects into intermediate-mass black holes. As estimated by Miller (2002), year-long LISA integrations are likely to detect several sources in our Galactic globular clusters within a few million years of merger, and several sources in globulars in the Virgo cluster of galaxies within a few thousand years of merger. The anticipated sources in Virgo are particularly interesting, for several reasons. First, the orbital frequencies are expected to be  $\gtrsim 10^{-3}$  Hz, which is a range relatively free from contamination by Galactic binary sources and most other known sources of noise, hence the signals should be comparatively clean. Second, the expected dynamical interactions and evolutionary paths of intermediate-mass black holes in clusters suggest that sources from the Virgo cluster will have detectable pericenter precession, orbital decay, and possibly Lense-Thirring precession (Miller 2002). Along with the orbital period and eccentricity (which can be derived from the waveform), this means that the gravitational wave signal alone will suffice to determine the distance to the Virgo cluster; alternately, assuming the distance as given, the orbital parameters will be overdetermined, leading to a strong self-consistency check of the expressions for the different post-Newtonian effects (Miller 2002).

*Inspiral of IMBH into supermassive black holes.*—As suggested by Madau & Rees (2001; see also de Araujo et al. 2002; Cutler & Thorne 2002), it is likely that some fraction of intermediate-mass black holes will eventually merge with the supermassive black hole at the center of their host galaxy. These events have similarities to the process of capturing stellar-mass compact objects by supermassive black holes, as considered by Sigurdsson & Rees (1997) and others. Such a merger would have a high mass ratio and would therefore come close to the test particle limit investigated in the context of stellar-mass black holes falling into supermassive black holes (e.g., Hughes 2001). These encounters are thought to have great promise for mapping out the three-dimensional spacetime near rotating black holes. If the small object is a  $\sim 10^3 M_\odot$  black hole instead of a  $10 M_\odot$  black hole, the orbits are still nearly those of test particles but the signal to noise ratio at a fixed luminosity distance is much greater. Therefore, if typically some tens of IMBH fall into a given supermassive black hole in a Hubble time, and there are therefore tens of events per year of this type that could be observed with LISA, this will provide extremely precise measurements of the spacetime.

## 7. Future Observations and Theory

It should be clear from this review that there are numerous fundamental issues about intermediate-mass black holes that have not reached consensus. There is reason for optimism that within a relatively short time, new observations and directed theoretical calculations will give us new insights and possibly resolve some of the current disputes. In this section, we suggest a number of such observations and theoretical developments.

*Radial velocity measurements.*—The only conventional astronomical way that the mass of ULXs can be constrained rigorously is by radial velocity measurements of stellar companions to

ULXs. For this to be definitive, one needs to (1) establish a periodicity for the X-rays, (2) identify an optical/UV/IR companion to the black hole that has the same orbital period as the periodicity in the X-rays, and (3) measure periodic Doppler shifts in the spectrum of the companion. This would produce a mass function, which is a lower limit on the mass of the black hole. If the mass function is  $M > 100 M_{\odot}$ , the object is definitely an IMBH, proving their existence. If the mass function is  $M \sim 10 M_{\odot}$  or less, then in principle the object could still be an IMBH (if, for example, the orbit of the companion is close to face-on to us). However, several examples of this type would lead rapidly to a negligible probability that all the sources were nearly face-on, and would therefore be strong evidence in favor of stellar-mass models. Even if no periodicity in X-rays is observed, a mass function  $M > 100 M_{\odot}$  would imply the existence of IMBHs, and one would logically associate the IMBH with the nearest ULX. For such searches it would be best to concentrate on the highest-flux ULXs rather than ones close to the fluxes of known stellar-mass X-ray binaries. Radial velocity measurements will be challenging because optical counterparts are dim (e.g., Liu et al. 2002b) and because early-type stars have weak lines in the optical.

*X-ray observations of ULX energy spectra.*—Now that high spectral resolution observations are available from *Chandra* and *XMM*, it is essential to revisit the spectra of the ULXs and determine whether the conclusions reached with *ASCA* data still apply. If indeed there is significant optically thick disk emission with temperatures  $kT > 1$  keV from high-flux ULXs, this argues in favor of low-mass models such as the beaming scenarios. If instead the disk temperatures are usually significantly lower than those of known stellar-mass black holes, or if alternate spectral models fit at least as well as the multicolor disk models, these conclusions need to be revised. A systematic study of these spectra would be valuable.

*X-ray timing observations.*—A potentially important type of X-ray analysis that has not yet been pursued extensively is timing measurements. In stellar-mass black hole candidates, there are characteristic bends in the power density spectrum that have been suggested as guides to the masses of the compact objects (see Cropper et al. 2003 for a promising application to NGC 4559 X-7). The lower the frequencies of these features, the higher the mass of the black hole. This may provide a strong discriminant between models of ULXs involving stellar-mass black holes and those involving intermediate-mass black holes. This is particularly true for models that involve relativistic beaming towards our line of sight, because relativistic effects would further increase observed characteristic frequencies. Timing on scales of tens of milliseconds would be ideal, but even archival *XMM* and *Chandra* data with readout times of a few seconds may be valuable. The benefits of this approach have already been demonstrated by Strohmayer & Mushotzky (2003), whose discovery of quasi-periodic oscillations (along with an Fe K $\alpha$  line) provide the strongest current evidence against beaming in an individual ULX.

*Multiwavelength observations of ULXs.*—Many of the most important observations of ULXs have come in the optical. These include associations with young stellar clusters (Zezas et al. 2002) or globular clusters (Angelini et al. 2001); the possible identification of a stellar companion in M81 (Liu et al. 2002); and the optical nebular emission in Holmberg II that may suggest

quasi-isotropic emission (Pakull & Mirioni 2002). There have also been a number of nondetections in radio wavelengths that may hold clues to the emission mechanism and whether or not many of these sources are beamed. Focused multiwavelength observations of ULXs are likely to provide additional breakthroughs. For example, if more stellar companions to ULXs are identified, it will determine whether the companions are always early-type stars, or whether in ellipticals limits on companions can be placed that suggest these are instead low-mass X-ray binaries.

Multiwavelength observations are also important to evaluate the broadband spectra of ULXs. Models with beaming tend to predict different spectra than models without, so UV/optical/IR/radio observations of particularly bright ULXs will be important. As more systematic studies of this type are performed, a clearer picture will emerge that can be compared to detailed spectral models.

Finally, multiwavelength observations may allow better estimates of the overall luminosities of ULXs, rather than just their isotropic equivalent luminosities. Optical emission from nebulae surrounding ULXs, as in the work of Pakull & Mirioni (2002), may be one path. It may also be possible to observe some molecular superbubbles to get upper limits to the energy input of the ULX itself; in some cases, if other energy sources can be neglected (e.g., early-type stars in a young cluster, or supernovae), an estimate of the energy output of the ULX may be obtained.

*Kinematics of globular clusters.*—Just as observations of the central regions of galaxies have provided strong evidence for supermassive black holes and the  $M - \sigma$  relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000a; Merritt & Ferrarese 2001a,b; Tremaine et al. 2002), observations of the kinematics of the central regions of globular clusters hold great promise for detection of massive black holes or meaningful upper limits on their presence. The current observations, while promising, do not yet have enough statistical significance to allow conclusions to be drawn. However, a sustained observational campaign to look at globulars with high central velocity dispersions (and thus, perhaps, high black hole masses) would be extremely valuable, regardless of the result. If no evidence for black holes is found, this will shed light on the limitations of the formation process and may guide research into the origin of the galactic  $M - \sigma$  relation. If black holes are found, this will be conclusive evidence for intermediate-mass black holes in the universe and will immediately have major implications for gravitational wave sources.

As discussed in § 3, an even more promising avenue may be detection of rotation in the cores of globulars. If such rotation exists, and if no explanation is found other than hardening of massive black binaries, then this evidence indicates both that IMBHs exist in the cores of globulars and that they are persistently and frequently merging with stellar-mass black hole or other compact remnants (see § 3). Proper motion data can augment radial velocity data significantly for both this type of observation and for searches for cusps, and analysis of such data is in progress (K. Gebhardt, personal communication; see also Drukier and Bailyn 2003).

*Tasks for models of ULXs.*—In this review we have discussed three different models for ULXs. In one, these are stellar-mass black holes that are beamed towards us, with luminosities less than

the Eddington luminosity. In the second, the flux distribution is quasi-isotropic, but the sources are stellar-mass black holes with luminosities many times the Eddington luminosity. In the third, the objects are intermediate-mass black holes emitting quasi-isotropically below the Eddington luminosity.

All three models need to be able to address observational or theoretical issues that have arisen in the last few years. If XMM and Chandra observations can be modeled to determine uniquely the temperature of the innermost portion of an optically thick disk, then a high temperature will pose problems for models in which the black hole mass is  $M > 10^2 M_\odot$ , whereas a low temperature would raise questions for stellar-mass models. There exist predictions for the multiwavelength spectrum (radio to X-ray) for various beamed and unbeamed models, which can be compared with data. Beaming models need to be able to account for the lack of variability on short timescales, which might have been expected by analogy to stellar-mass black holes in the Galaxy. Super-Eddington models need to be explored more to determine the conditions for such emission to occur in real disks, and to derive other observational signatures that could be used to check the interpretation. In models with  $M > 10^2 M_\odot$ , more details need to be understood about how such objects form. For example, can zero-metallicity (Population III) stars really have hundreds of solar masses? If the objects are formed dynamically, then in detail can the inferred masses be reached for the known central densities and populations of young or old clusters? When partnered with observations, there is much reason for optimism that many of these issues will be resolved in the next few years.

*Gravitational waves.*—If intermediate-mass black holes exist in the cores of many dense star clusters, one of their most exciting implications is for the generation of gravitational waves. In addition to the dynamical simulations discussed above, this may pose new challenges for numerical simulations of mergers. A stellar-mass compact object merging with an intermediate-mass black hole does so with a mass ratio of  $\sim 10 : 1$  to  $\sim 1000 : 1$ . Such mass ratios, particularly at the low end of this range, are not large enough that the less massive object can be considered as a test particle to high precision. However, the interactions are likely to be less complicated to simulate than equal-mass mergers. This may therefore provide a bridge calculation on which to test numerical codes.

Finally, we note that debate on the nature of IMBHs will undoubtedly continue until rigorous measurements of the masses of IMBHs are possible. If radial velocity measurements are impractical because of the low fluxes from stars at the distance of ULXs, then the only other way to measure the mass beyond doubt is to observe the gravitational waves from the inspiral of a compact object into an IMBH. If so, then IMBHs are, remarkably, one of the small set of objects in the universe whose proof of existence requires detection of their gravitational radiation emission.

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